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CRASH TESTING OF VARIOUS EROSION CONTROL FEATURES – PHASE I: PRELIMINARY GUIDELINES

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In recent years, greater attention has been placed on controlling erosion and improving the quality of water runoff that leaves the right of way found along roads. As a result, riprap, rock check dams, ditch liners, and other devices have been more frequently installed within and/or adjacent to the roadside. Unfortunately, very little to no research has been performed in order to determine the crashworthiness of the erosion control features noted above. A clear need existed to investigate the crashworthiness of selected erosion control features, such as ditch liners and check dams, when used in combination with sloped drainage features.

The design practices employed by 14 different state departments of transportation regarding these devices were examined as well as national guidelines set forth by various federal agencies for similar structures. Key safety considerations were noted during the investigation, from which preliminary guidelines for the safe design and placement of rock check dams and rock ditch liners were developed. A plan involving the refinement of these guidelines through future computer simulation (Phase II) and full-scale testing (Phase III) research was also developed.

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1 INTRODUCTION

1.1 Problem Statement

In recent years, greater attention has been placed on controlling erosion and improving the quality of water runoff that leaves the right of way found along roads. As a result, riprap, rock check dams, ditch liners, and other devices have been more frequently installed within and/or adjacent to the roadside. Unfortunately, very little to no research has been performed in order to determine the crashworthiness of the erosion control features noted above.

The American Association of State Highway and Transportation Officials (AASHTO) *A Policy on Geometric Design of Highways and Streets* [1] contains general guidance regarding the safe use of roadside hardware, drainage features (i.e., drainage channels, ditches, and curbs), and roadside geometries, such as side slopes. However, the AASHTO document provides no specific guidance regarding the crashworthiness of many common erosion control features, such as ditch liners and check dams. The 2006 AASHTO *Roadside Design Guide* [2] also addresses the crashworthiness of selected drainage features, such as drainage channels, ditches, curbs, and culvert openings. Unfortunately, no significant guidance exists regarding the safe design and placement of roadside channels and ditches incorporating erosion control features, such as ditch liners and check dams.

State Departments of Transportation (DOTs) often expend significant financial resources on highway and road construction projects addressing safety concerns associated with the design and layout of clear zones, especially when considering roadside drainage and water quality. In these situations, agencies must balance safety and environmental concerns. As such, ditch liners and check dams are occasionally used within clear zones to mitigate environmental concerns associated to degraded water quality even though there are no clear guidelines regarding their safety performance. There exists a need to investigate the crashworthiness of selected erosion control features, such as ditch liners and check dams, when used in combination with sloped drainage features. In addition, preliminary safety guidelines are needed to assist engineers with the design and placement of erosion control features.

1.2 Research Objective

The primary research objective for this study included the development of safety guidelines for use in the design and placement of ditch liners and check dams along highways and roadways. For Phase I and as part of the initial research funding, preliminary safety guidelines were to be proposed along with a preparation of a research plan for use in their future evaluation. If the Wisconsin Department of Transportation deemed the preliminary guidelines viable, then the potential would exist for additional research study phases to be funded to support the evaluation and modification of the guidelines using full-scale crash testing and/or computer simulation.

1.3 Research Plan

As noted above, this research effort was to be conducted in separate phases. The Phase I effort included the development of preliminary guidelines regarding the safe design and placement of selected erosion control features as well as the preparation of a research plan to evaluate the initial guidelines. Subsequent phases would include the actual crash testing and computer simulation effort as well as the modification of the guidelines, as deemed necessary.

1.3.1 Phase I – Preliminary Guidelines

For this study, a review of existing guidelines regarding the design and placement of erosion control features was performed for the member of the Midwest States Pooled Fund Program, including documents pertaining to the use of check dams and ditch liners. Next, a literature review was conducted regarding the crashworthiness of drainage features through either crash testing or computer simulation. It should be noted that no direct crash testing studies contained vehicular impacts with check dams and ditch liners. As a result, some correlations to similar features and geometries were deemed necessary. Based on prior research and existing State DOT guidelines, preliminary guidelines were prepared as a function of highway speed and for use in designing and placing ditch liners and checks dams. These preliminary guidelines were prepared to assist engineers with configuring a safe roadside while simultaneously minimizing roadside erosion.

A research plan was developed for evaluating the safety performance of critical configurations of rock ditch liners and rock check dams using computer simulation and full-scale vehicle crash testing.

1.3.2 Future Phases – Evaluation of Guidelines: Crash Testing & Simulation

The subsequent future phases of this study will consist of the actual evaluation of the guidelines using crash testing and computer simulation, as mentioned in Phase I. These phases will only be completed if the Wisconsin Department of Transportation finds that the preliminary guidelines presented herein meet their needs for controlling erosion along highways and roads.

2 BACKGROUND

2.1 Introduction

Erosion control measures have been used extensively throughout the nation's road infrastructure to protect the integrity of the roadway and its corresponding roadside cross sections. Factors that encourage the use of these features include, but are not limited to, the type of soil and the natural grade of the land itself. Roadsides composed of silty soils with relatively steep grades are highly susceptible to the effects of water runoff and bear the consequence of an increased propensity for soil erosion. In most cases, it would not be economically feasible to drastically alter the configuration of the landscape itself. Instead, an erosion control feature is incorporated into the roadside terrain to increase its resistance to the effects of water runoff. Although these features work extremely well in slowing the flow of water and in protecting the surface of the roadside, caution should be taken when their placement falls within the clear zone. This research study focused on two commonly-used and potentially dangerous structures found along roadsides – rock check dams and rock ditch liners. Examples of these objects are provided in Figure 1.

Figure 1. Roadside Rock Check Dams (above) and a Rock Ditch Liner (below)

2.2 AASHTO Guidelines on Erosion Control and Drainage Devices

The AASHTO road design manuals - *A Policy on Geometric Design of Highways and Streets* [1] and *Roadside Design Guide* [2] – do not include general guidelines pertaining to the safe design of erosion control features, such as ditch liners and check dams. Thus, the geometry and layout for these erosion control features vary widely from state to state. However, these AASHTO documents do provide general guidelines for some drainage devices (i.e., ditches, channels, and curbs) as well as for roadside slopes found. As such, these general guidelines may provide insight into the overall design of ditch liners and check dams when used to mitigate soil erosion near highways and roadways. The relevant design guidelines pertaining to these roadside safety features are summarized in the following sections.

Two other non-road design AASHTO manuals provide information pertaining to erosion control features, such as ditch liners and check dams. However, the general guidance pertaining to roadside safety is scarce as both documents focus primarily on the hydraulic functions of these features. AASHTO's *Highway Drainage Manual* [3] states that grade-control structures, such as rock check dams, "are not recommended for use in roadside ditches unless they are located outside a safe recovery area or protected by guardrail of other appropriate safety barriers." Second, AASHTO's *Model Drainage Manual* [4], denotes the vagueness of the AASHTO guidelines for erosion control features by stating "Although some standardization of methods for minimizing soil erosion in highway construction is possible, national guidelines for erosion control are of a general nature because of the wide variation in climate, topography, geology, soils, vegetation, water resources and land use encountered in different parts of the nation." This statement demonstrates the difficulty involved with creating a standard set of guidelines which are to be followed by various states.

2.2.1 Ditches and Side Slopes

Drainage channels should be located and shaped to provide a safe transition from the roadway, front slope, and through the back slope. This region should be reasonably flat, smooth, and free of fixed objects. In general, traversable slopes along the channel sides should be 1V:3H or flatter, with a desirable steepness of 1V:6H. A clear runout length should also be incorporated at the toe of any front slope between 1V:3H and 1V:4H. Any slopes steeper than 1V:3H would decrease the recovery distance for an errant vehicle as well as increase the propensity for vehicle rollover. Also, drainage channels should be protected against erosion with a cost-effective protective lining that will withstand the expected flow velocities and with stone listed as an acceptable alternative.

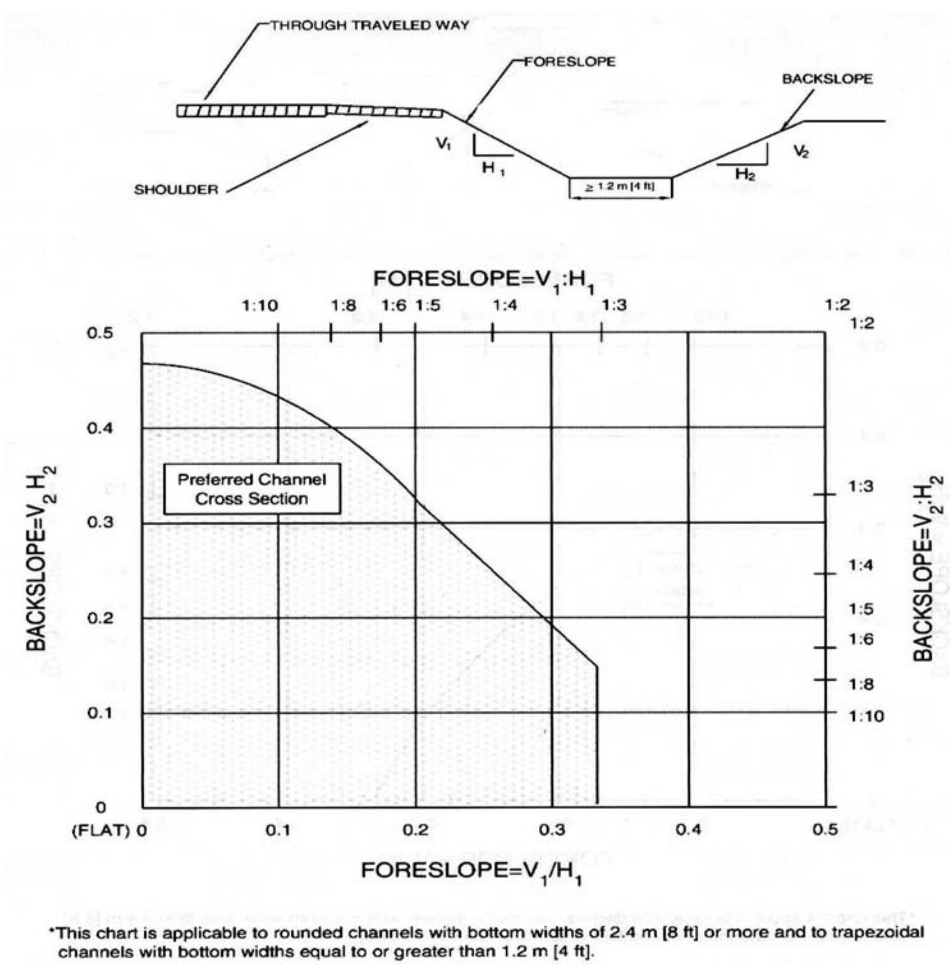

Figure 2. AASHTO Flat Bottom Ditch Guidance [2]

2.2.2 Parallel-Drainage Structures

Parallel-drainage structures are typically located in median crossover driveways and are used to convey water under the road to an adjacent outlet. These structures are oriented parallel to the flow of traffic. Figure 3 depicts the general configuration for a parallel-drainage structure. The structure slope is generally deemed more critical than side slopes because errant vehicles are likely to hit them head on. These approach slopes should be 1V:6H or flatter, with a desirable steepness of 1V:10H. These structures should also match the adjacent median slopes using a smooth transition.

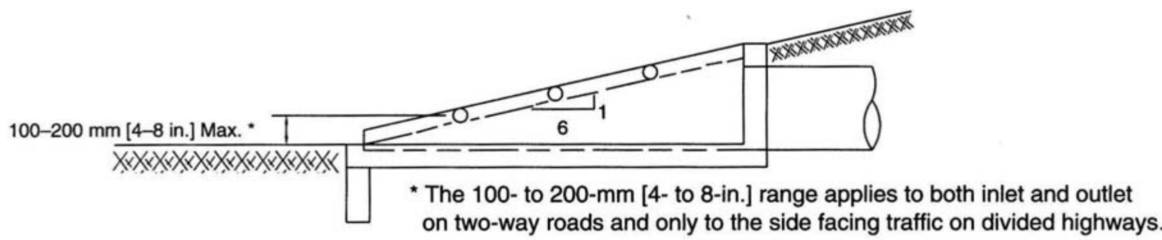

Figure 3. AASHTO Parallel-Drain Guidance [2]

2.2.3 Cross-Drainage Structures

The function and design of cross-drainage structures are very similar to that of parallel-drainage structures. However, cross-drainage structures are oriented perpendicular to the flow of traffic and lay in ditch side slopes rather than within median crossover roads and slopes. Cross-drainage structures should be shortened or extended accordingly to intercept the roadway embankment and match the corresponding fill slope. These structures should be designed to be smooth and flat as possible.

2.2.4 Curbs

There are two different categories of curb configurations in use today – vertical and sloping. Vertical curbs range from 6 to 8 in. tall and are intended to discourage drivers from crossing them. Sloping curbs range from 4 to 6 in. tall and are designed to be readily traversed by motorists, when necessary. In general, these curb types have inadequate capability to redirect errant vehicles under most impact conditions and are not recommended for use along high-speed roadways due to the propensity to result in vehicle overturn during side impacts.

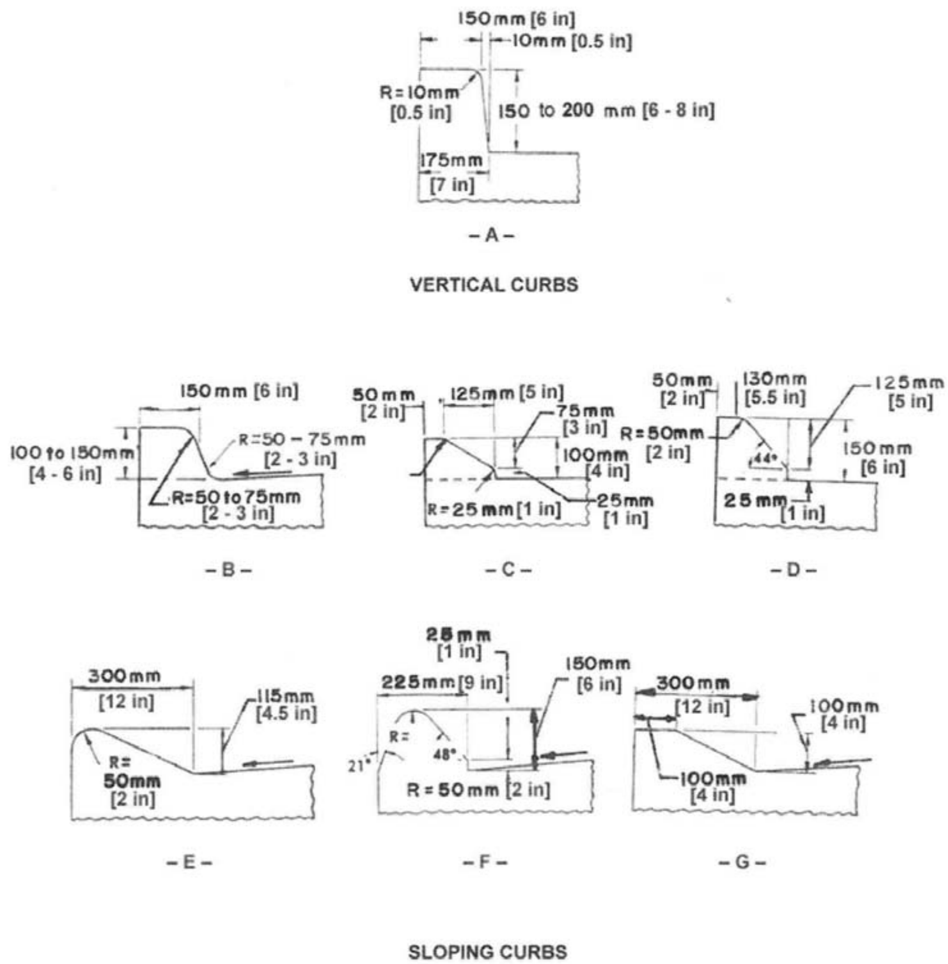

Figure 4. AASHTO Typical Highway Curbs [1]

It should be noted that whenever it is not possible to provide the minimum design standards for many of the features noted above, a roadside barrier is often recommended for installation to shield the hazardous feature.

2.3 State DOT Guidelines

2.3.1 Rock Check Dams

As stated previously, the main purpose of a rock check dam is to control the flow of water leaving the roadside and entering a drainage channel or ditch. Regardless of the particular design, these devices generally have the same overall layout with a few differences in geometry. Typically, rock check dams are constructed of irregular rocks varying in size from 4 to 8 in. These rocks are usually placed in such a manner as to partially extend down one side of the ditch and up the other side, containing a dip in the center region. This design practice forces water to flow over the structure rather than around it, eliminating the possibility of scour along the ditch sides and further reducing the degradation of the ditch. For example, the base design presented by the Federal Highway Administration (FHWA) in the document titled, *Best Management Practices for Erosion and Sediment Control* [5] depicts a 2-ft high dam with a 6-in. dip in the midpoint as compared to the end regions, constructed from 6-in. rock, and having 1V:2H face slopes.

The common practice for installing a check dam is to place the subsequent dam so that the low point of its dip is in line with the previous dam toe. Consequently, the actual longitudinal spacing between consecutive rock check dams is completely dependent upon the grade of the drainage channel. For example, ditches with steeper grades would require a greater number of rock check dams, thus resulting in a reduced longitudinal spacing.

The two major deviations in the design of these devices are the height of the check dam and the slope of the dam face perpendicular to the flow of water. Specific examples taken from several State DOT standard plans are provided in Appendix A. As shown in Table 1, the general practice for implementing rock check dams along with important safety characteristics are summarized for each State DOT which responded to the survey. The wide variance in policies further demonstrates the need to develop a single set of design and implementation guidelines.

Table 1. Summary of State DOT Guidelines for Rock Check Dams

State DOT	Drawing No.	Reference No.	Center Height of Dam (in.)	Minimum Size of Dip (in.)	Maximum Face Slope (V:H)	Rock Size (in.)	Safety Details
California	SC-4	[6]	30[1]	6	1:3	12[1]	N/A
Illinois	212-280001-05	[7]	36[1]	6	1:2	varies[4]	Traffic approach slope shall be 1V:4H in the clear zone.
Iowa	4401	[8]	-	-	-	6[3]	N/A
Kansas	LA852G	[9]	20[1]	4	1:1	6[3]	Do not place in the clear zone.
Minnesota	5-297.405	[10]	30[1]	6	1:2	varies[4]	Maximum height will be 18" and slope 1V:6H in clear zone.
Missouri	806.10H	[11]	18[2]	6	1:2	6[3]	If located in the clear zone, rock check shall be removed after vegetation has sufficiently matured.
Nebraska	-	-	-	-	-	-	N/A
New York (temporary)	EB-08-036	[12]	24[1]	9	1:2	varies[4]	N/A
New York (permanent)	EB-08-036	[12]	12[1]	9	1:6	6[3]	Permanent stone check dams located within the established roadway clear zone shall be in conformance with NYSDOT Roadside Design Guidance.
Ohio	DM-4.4	[13]	24[2]	6	-	8[1]	N/A
South Dakota	734.03	[14]	18[1]	6	1:6	-	N/A
Texas	EC (2) - 93	[15]	24[1]	12	1:2	8[1]	Dams within the safety zone shall have side slopes of 1V:6H or flatter.
Virginia	EC - 4	[16]	36[1]	6	1:2	varies[4]	If check dam is located inside of clear zone and adjacent to a travel way, slope facing oncoming traffic is to be 1V:6H with a maximum height of 12 in.
Wisconsin		[17]	30[1]	6		5[1]	N/A
Wyoming	215-1	[18]	12[2]	6	1:2	6[1]	Rock ditch checks will not be allowed within the limits of the clear zone.

[1] Maximum [2] Minimum

[3] D_{50} - half of the rocks will be smaller than this size.

[4] A layer of smaller stone is placed on the flow approach slope with larger riprap behind.

2.3.2 Rock Ditch Liners

Rock ditch liners are used in areas that experience high or fast flowing water along the roadside. These features are considered flexible due to their ability to adjust to foundation changes, unlike more expensive rigid liners, such as concrete pavement, which have a tendency to fail from undermining. According to the State DOT responses, the analysis of rock ditch liners considers the permissible shear stress acting along the bed of the ditch and that is produced by the water flow. The permissible shear stress is highly affected by the shape and grade of the ditch. This philosophy and subsequent design guidelines were set forth by FWHA in the Hydraulic Engineering Circular Nos. 11 and 15 [19-20] which address the selection of rock size for use as a lining material to resist displacement from water pressure. Note that material size affects the overall liner thickness.

A second FHWA document entitled, *Maintenance of Drainage Features for Safety – A Guide for Local Street and Highway Maintenance Personnel* [21] does very briefly address the safety of side slopes, including riprap and ditch linings. Specifically, it denotes that side slopes should be smooth, free of fixed objects, and free of snagging features. Vehicles traveling down slopes are difficult to control and may strike, roll over, or drop into a feature, which can cause a vehicle to abruptly halt, become unstable and roll over, or strike the back slope. Erosion scars on a side slope can also initiate vehicular instabilities by tripping the wheels and causing rollover. As such, erosion scars should be graded and seeded. If riprap is used to control and spread the flow of water, it should have shallow inverts and be placed flush with the existing ground. Specifically, rock and stone ditch linings should be smooth and not "bumpy" so that a driver can regain control of the vehicle.

In addition to the basic FHWA guidelines, different State DOT procedures are available regarding the construction of rock ditch liners. Unfortunately, these procedures are often open to significant engineering and construction judgment. As mentioned previously, the wide variance of characteristics associated with ditch geometries, soil characteristics, and water quantities from site to site make it very difficult to generate a standard set of design guidelines for ditch liners. As suggested by FHWA, three separate methods exist for riprap placement in roadside ditches and are as follows:

1. Dumped riprap – riprap is dumped into the ditch by means of a truck, keeping care to maintain rock gradations. This placement method can include the option for the riprap to be plated by dropping a large metal sheet onto the liner to produce a more uniform grade.

2. Wire enclosed riprap – riprap is placed into wire baskets along the ditch. This method allows for the use of smaller rock.

3. Grouted riprap – riprap is placed into the ditch, and then the voids between the rocks are filled with Portland cement. This method creates a more rigid liner that can experience higher flows.

Some common placement practices exercised by the State DOTs are also listed below:

1. Place stones in such a manner as to create a well-graded, flexible mass of stones with minimal voids. The use of grout to fill the remaining voids is optional.

2. The terrain of the ditch should be undercut, and the contours of the liner should match that of the existing grade. This guidance will help to keep the liner free of any raised bumps or depressions. This goal is also achieved by the State DOTs through the practice of encasing the liner in a wire mesh or by plating the riprap.

3. The liner should consist of stones that are angular in shape in order to create an interlocking mechanism when dumped or hand placed, thus reducing the possibility of deformation to any portion of the liner.

A more detailed summary of the feature geometries presented by each of the State DOTs examined is listed in Table 2. Although the dumping of rocks into a ditch does not intuitively seem like a task that would require much precision, the State DOT guidance contains minimal standard dimensioning with an allowance to follow wide ranges. This guidance could obviously result in a lack of consistency from one rock ditch liner to another, even along the same stretch of roadway, thus creating a very complex situation to examine.

Table 2. Summary of State DOT Guidelines for Rock Ditch Liners

State DOT	Drawing No.	Reference Manual	Predominant Rock Size (in.)	Minimum Thickness of Liner (in.)	Suggested Side Slope (V:H)	Safety Details
California	Rock Blanket [22]	Roadside Management Toolbox	4 - 6	6	-	Rock blanket may be placed within the clear zone if rock is mortared in place or barrier between roadway and blanket exists.
Illinois		2007 Specifications, Division 200 & 1000	5 - 16	8	-	N/A
Iowa	4402 [8]	2009 Specifications, Section 2507 & 4130	6 - 15	24	1:2	N/A
Kansas	RD502 [9]	Drainage, Section 12.7	4 - 12	12	1:6	Aggregate larger than 6 in. should not be used in the clear zone.
Minnesota		2005 Specifications, Section 2511 & 3601	9 - 15	12	-	N/A
Missouri	609.60C [11]	2004 Specifications, Section 609	3 - 19	8	-	N/A
Nebraska		Drainage Design, Section 7	9 - 15	18	-	N/A
New York		Stormwater Facilities, Region 8	6	12	1:3	N/A
Ohio		2010 Specifications, Item 703 & 1100	6 - 18	12	-	Rock channel protection may be used to line the ditch if the nearest point of the lining is outside the design clear zone or located behind guardrail or barrier.
South Dakota[1]		Road Design, Chapter 11	-	-	-	N/A
Texas		2004 Specifications, Section 432	9 - 21	12	-	N/A
Virginia	PG-3 [16]	2007 Specifications, Section 414	15 (max)	20	-	N/A
Wisconsin		2010 Specifications, Section 606	4 - 18	12	-	Clear zone requirements must be examined.
Wyoming	511-1A [18]		3	9	-	Wire enclosed. Protrusions greater than 4 in. are not allowed.

[1] No standards. Based on site to site assessment.

The California Department of Transportation (CALTRANS) guidance provides a detailed description for the implementation of rock ditch liners, leaving little room for onsite judgment [22]. As shown in Figure 5, the CALTRANS specifications require a “blanket” of 4- to 8-in. rock embedded in a minimum 4-in. thick concrete base. The majority of each rock is set in the concrete base, while the remaining free portions of the rock are mortared in order to create a relatively smooth, uniform surface. If desired, a 6-in. high extruding concrete header may be placed at the edge of the rock blanket. The specifications also clearly note that rock blankets shall not be placed within clear recovery zones that are subject to errant vehicles unless mortared into place or shielded with a barrier, and the placement of rock blankets should be kept from pedestrian access due to the hazardous possibility of removal or vandalism.

Although the rock blanket ditch liner appears to have a higher cost ($\$85/yd^2$ - $\$120/yd^2$) than the conventional method of just dumping rocks ($\$25/yd^2$ - $\$85/yd^2$), it does have the benefit of reducing the roughness of the liner itself. It should be noted that roughness of terrain is a major consideration when investigating the maneuvers of an errant vehicle. Later, the effects of increased roughness of terrain and higher coefficients of friction for vehicle tires will be discussed as to their direct correlation to the likeliness of vehicular instabilities.

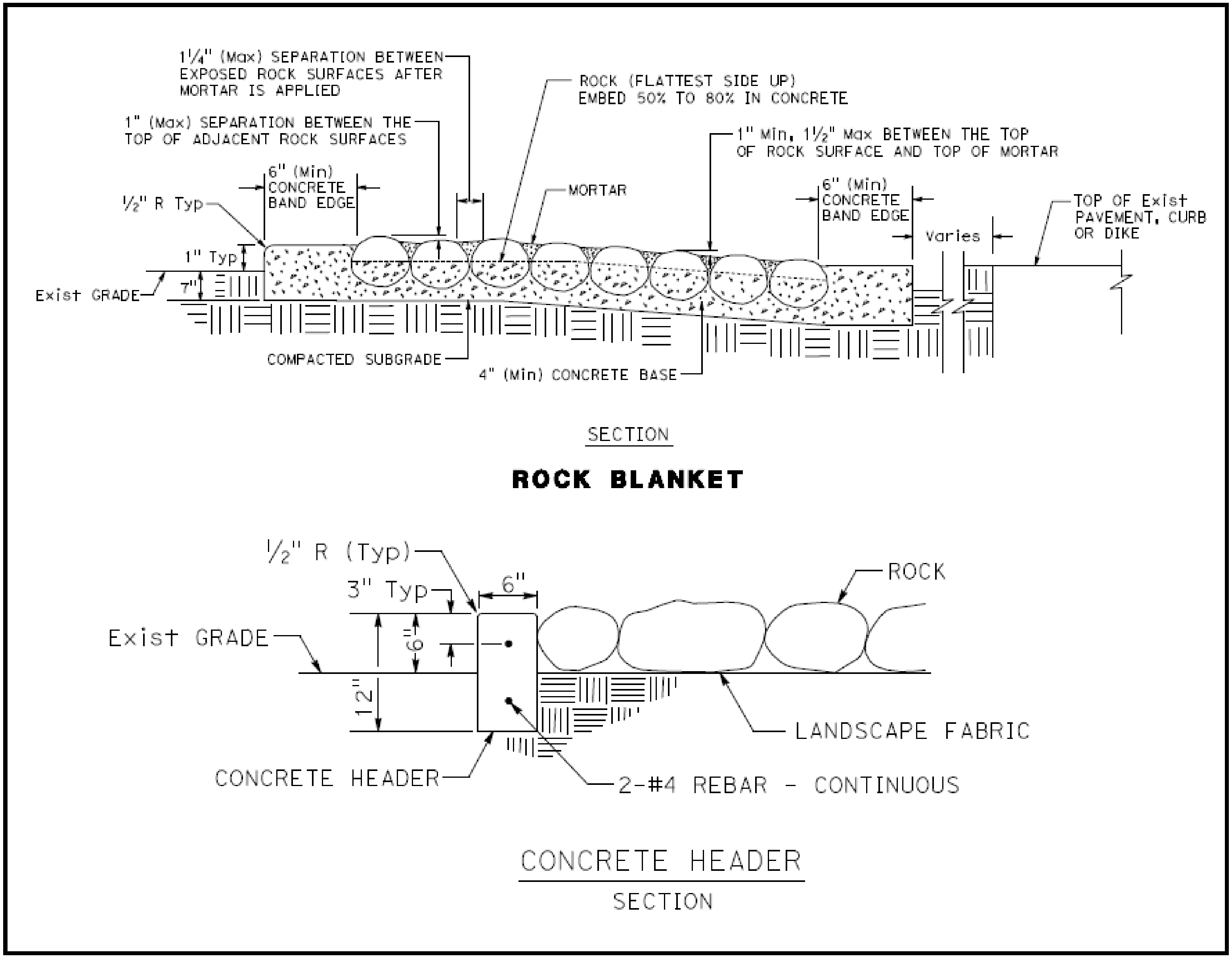

Figure 5. California Rock Blanket Details [22]

3 LITERATURE REVIEW

3.1 Overview

An extensive literature review was performed on the safety performance of rock check dams and rock ditch liners used as erosion control along highways and roads. From this review and to date, no direct crash testing or computer simulation programs have been conducted to investigate the crashworthiness of these features when subjected to vehicular impacts. Most road engineers and designers would agree that the concentrated placement of large rocks along the road potentially poses undue risk to motorists and errant vehicles. Unfortunately, the extent of this safety hazard is largely unknown.

Several drainage structures (i.e., slopes, drainage channels, ditches, and curbs) are in use today for which the crashworthiness is relatively known and well-documented for vehicular crashes involving tracking impact conditions. As a result, these drainage features have become somewhat standardized through the crash testing and computer simulation efforts. Therefore, the research team believed that a vehicle's ability to safely traverse slopes, ditches, channels and curbs may provide insight into the behavior of vehicles traversing ditch liners and check dams.

A review of the key research studies as well as the corresponding findings that led to the standardized features and implementation practices are discussed in the following sections.

3.2 Roadside Slope and Ditch Research

In 1972, researchers at the Texas Transportation Institute (TTI) conducted a full-scale crash testing and computer simulation validation study of vehicle traversals on a 1V:3.5H fill slope with flat bottom ditch located approximately 20 ft below roadway [23-24]. Six actual crash tests were performed with a 1963 Ford Galaxy with speeds ranging between 45.1 and 63.6 mph and angles ranging between 8.6 and 20.4 degrees. Computer simulations were performed with the Highway Vehicle Objective Simulation Model (HVOSM) and used for comparison to the actual crash test results [25-26]. From the study, the researchers concluded that an automobile and its occupants can safely traverse a 1V:3.5H side slope with a flat bottom ditch located 20 ft below the roadway with relative ease and tolerable accelerations for a wide variety of encroachment conditions.

In 1975, Texas Transportation Institute (TTI) researchers again examined the safety performance of various roadside slope cross sections through the use of computer simulation and full-scale vehicle crash testing [27-29]. Computer simulations were performed with the Highway Vehicle Objective Simulation Model (HVOSM) [30] using both free-wheeling and steer-input traversals within various ditch configurations and with a 1963 Ford Galaxie. Roadside slopes, ranging from 1V:3H to 1V:10H, were simulated and evaluated using different coefficients of friction and at speeds of 40, 60, and 80 mph with encroachment angles of 7, 15, and 25 degrees. The study also utilized 24 full-scale vehicle crash tests to validate the simulation results. The crash tests were performed on slope combinations of 1V:3H to 1V:5H forming round and vee ditches. The tests were conducted at speeds of 30, 40, 50, and 60 mph with an encroachment angle of 25 degrees and using 2-door and 4-door, 1963 Ford Galaxies weighing approximately 3,830 lbs and 3,820-lbs, respectively.

Two criteria were used to evaluate each traversal test - vehicle rollover and vehicle accelerations in each of the principal axes. These corresponding accelerations were used in the following equation to produce a Severity Index (SI).

$$SI = \sqrt{\left(\frac{G_{lon}}{G_{xl}}\right)^2 + \left(\frac{G_{lat}}{G_{yt}}\right)^2 + \left(\frac{G_{ver}}{G_{zl}}\right)^2}$$

where

SI = Severity index
G_{lon} = Acceleration experienced in longitudinal axis, G's
G_{lat} = Acceleration experienced in lateral axis, G's
G_{ver} = Acceleration experienced in the vertical axis, G's

G_{xl} = Tolerable acceleration in longitudinal (X-axis) direction, G's
G_{yl} = Tolerable acceleration in lateral (Y-axis) direction, G's
G_{zl} = Tolerable acceleration in vertical (Z-axis) direction, G's

The tolerable acceleration limits used in this study were developed by Hyde [31] and are shown in Table 3. Conclusions were made regarding the safety performance of various combinations of slopes and impact conditions as well as were based on using an unrestrained passenger. Further, a severity index equal to 1.0 or less was deemed acceptable and tolerable for an unrestrained occupant, while a severity index equal to 1.6 was deemed the upper limit for an occupant using a seat belt restraint system.

Table 3. Tolerable Acceleration Limits

	Maximum Acceleration (g's)		
Restraint Configuration	Lateral G_y	Longitudinal G_x	Vertical G_z
None	5	7	6
Lap belt	9	12	10
Lap belt and shoulder	15	20	17

The crash tests and a majority of the computer simulations were conducted on ditch sections with smooth surfaces (i.e., even terrain). Under these actual and simulated test conditions using smooth surfaces, no vehicle rollover occurred on any of the slope configurations for all encroachment speeds and angles. This result was true regardless of the steer condition. It should be noted that the simulation results were extrapolated to illustrate that a vehicle encountering a 1V:2H embankment at a speed equal to or in excess of 80 mph would likely result in rollover.

As a purely smooth surface represents only an ideal condition, alternate computer simulations were conducted to examine the effects of irregular surface conditions that often develop after initial construction, such as deep tire ruts or erosion washouts. In addition, other factors were investigated which may contribute to vehicle overturn, such as critical combinations of side slope, velocity, time at which steer-back maneuver initiated, and slope irregularities. The irregularities included coefficient of friction, vertical raises placed in the slope, vertical drops (i.e., ruts) placed in the slope, and sloping rise in the slope.

For the special slope conditions noted above, the following observations were made. In terms of speed, vehicle rollover occurred at speeds of 60 and 80 mph for an encroachment angle of 15 degrees for several slope irregularities. No rollover occurred at speeds of 40 mph or at an encroachment angle of 7 degrees. In terms of front slope steepness, vehicle rollover occurred on slopes of 1V:2H, 1V:3H, and 1V:4H for several combinations of conditions. However, no rollover occurred on slopes of 1V:5H or flatter. Both negative (ruts) and positive (curbs) rises were simulated. When passing over a 6-in. rut, a simulate vehicle encountered little change in direction or roll characteristics even with a full 30-degree steer input. However, the simulated vehicle bottomed out, slowed appreciably, and change direction slightly on a 9-in. rut. For a 6-in. curb, the simulated vehicle rolled over at speeds of 60 mph or greater and when placed on a 1V:3H slope. In terms of a sloping rise, a special scenario was simulated which involved a rising slope of 1V:2H for 2 ft, then dropping to 1V:3H slope. At 80 mph, vehicle rollover occurred on the 1V:3H fill slope. At 60 mph, the vehicle roll angle reached 52 degrees and then stabilized on all four wheels. A select listing of these corresponding test conditions and results can be found in Table 4. Notable conclusions made from this study are listed below:

1. Return maneuvers can be accomplished without vehicle rollover on smooth, firm embankments 1V:3H or flatter at speeds up to 80 mph and encroachment angles of 15 degrees.

2. To permit recovery, embankment surfaces must be relatively uniform.

3. Vehicle rollover can be expected for return maneuvers attempted above 60 mph if the embankment is rutted.

4. Front slopes steeper than 1V:4H are not desirable. Slopes steeper than 1V:3H are recommended only where site conditions preclude the use of flatter slopes.

5. The trapezoidal ditch configuration represents the most desirable cross section from a safety standpoint, particularly for ditches wider than 8 ft.

In 1985, TTI researchers completed a crash testing and computer simulation effort to evaluate additional vehicles traversing roadside slopes [32-33]. The primary objective of this study was to continue the slope traversal testing program that was completed in 1975 but with using different vehicle types - a 4,450-lb Ford pickup truck, a 4,120-lb Dodge van, and a 1,938-lb Honda Civic small car. Full-scale vehicle crash tests were performed on a 1V:3H fill slope with a 15-ft embankment height. Each vehicle left the roadway at a 15-degrees encroachment angle and traveling at speed of approximately 50 mph. Return maneuvers were attempted in each case. Both the pickup truck and the van were able to return to the roadway with some degree of sideslip, but the car encountered enough sideslip for it to reach the toe of the slope and ultimately rollover. The conclusions drawn from the test were similar to conclusions made from the 1975 study. Smooth, well-compacted slopes as steep as 1V:3H can be traversed safely, but small discontinuities along the slope are highly likely to upset the stability of the vehicle.

HVOSM computer simulations were also performed on three different embankment slopes, 1V:3H, 1V:4H, and 1V:6H, at speeds of 60 mph, at encroachment angles of 15 and 25 degrees, and using a coefficient of friction of 0.5. No vehicle rollover was observed for the noted impact conditions. From the simulation results, TTI researchers concluded that the small car and specialty vehicles are not particularly unstable on smooth, well-compacted roadside slopes of 1V:3H or flatter.

In 1986, Calspan Corporation researchers studied vehicle interaction with various roadside features in order to determine critical design criteria based on the potential for inducing vehicle rollover [34-35]. As part of this study, full-scale vehicle crash tests were performed to determine tire/ground coefficient of friction for typical roadside terrain surface, spinning skid behavior for small cars, as well as the ability for small cars to traverse fill slopes and ditch embankments at moderate speeds and with steer imparted to the vehicle. VW Rabbits, weighing 2,410 lbs including driver, were used for these validation tests. In this testing program, no small car rollovers were observed. These vehicle tests were then used to validate HVOSM computer simulations as well as to evaluate various roadside terrain under tracking and non-tracking departures. Three vehicle types were considered – a 2,410-lb VW Rabbit, an 1,800-lb VW Rabbit, and a 4,540-lb large passenger sedan. Two impact conditions were simulated. The first departure condition used a speed of 60 mph, a path angle of 15 degrees, and a sideslipe angle of 0 degrees, while the second condition used a speed of 45 mph, a path angle of 25 degrees, and a sideslipe angle of 30 degrees. From this study, the authors made several key conclusions and recommendations, including:

1. Fill embankments should be no steeper than 1V:3H, and preferably flatter, to reduce likelihood of rollover. Results from tests and computer simulations show that 1V:3H slopes are marginally safe for traversal of small, lightweight automobiles. Slopes should be firm and smooth to minimize potential for vehicle's tires to dig into ground or strike surface irregularity which could trip the vehicle into a rollover.

2. Ditches having front slopes no steeper than 1V:3H appear relatively safer with respect to vehicle rollover potential.

3. All slope breaks of roadside terrain should be rounded as much as possible to reduce the potential for vehicles to rollover due to tripping on sag vertical curves.

More recently and in 2002, Thomson and Valtonen [36] conducted a significant study to examine the vehicle dynamics encountered while traversing a roadside V-shaped ditch. A 3.3-ft (1-m) deep ditch was constructed with a 1V:3H front slope and a 1V:2H back slope. A total of

16 full scale crash tests were performed on this ditch configuration – 14 with a 1,984-lb (900-kg) vehicle and 2 with a 3,307-lb (1,500-kg) vehicle. The impact speeds ranged from 38.5 to 66.5 mph (62 to 107 km/h), while the encroachment angles ranged from 3 to 20 degrees. Moderately severe tests resulted in peak vehicle accelerations of about 5 g, while the most severe tests resulted in peak vehicle accelerations of about 15 g. For tests 1 through 14, three vehicle rollovers were observed with the 1,984-lb (900-kg) small car at the following conditions: 79 km/h and 20 degrees; 107 km/h and 19 degrees; and 82 km/hr and 11 degrees.

In addition, the V-shaped ditch was also evaluated with two different surface irregularities in the last two tests in this series, as indicated in Figure 6. For test 15, the V-shaped ditch was modified into a U-shaped ditch by lining the bottom of the ditch with loose gravel. The test vehicle, traveling at 60 mph (96 km/h) and set at a 10 degree encroachment angle, had no trouble traversing the configuration and climbing up the back slope. For test 16, a vertical barrier was installed near the toe of the back slope. In this case, the vehicle impacted at a speed of 62 mph (100 km/h) and at a 10-degree encroachment angle, then it violently rolled over as it came into contact with the barrier on the back slope. In general, the researchers noted that small cars were observed to roll over for impact angles of 10 degrees and impact speeds of about 80 km/h. Also, vehicle rollover was believed to be a direct result of contact with the back slope of the V-shaped ditch.

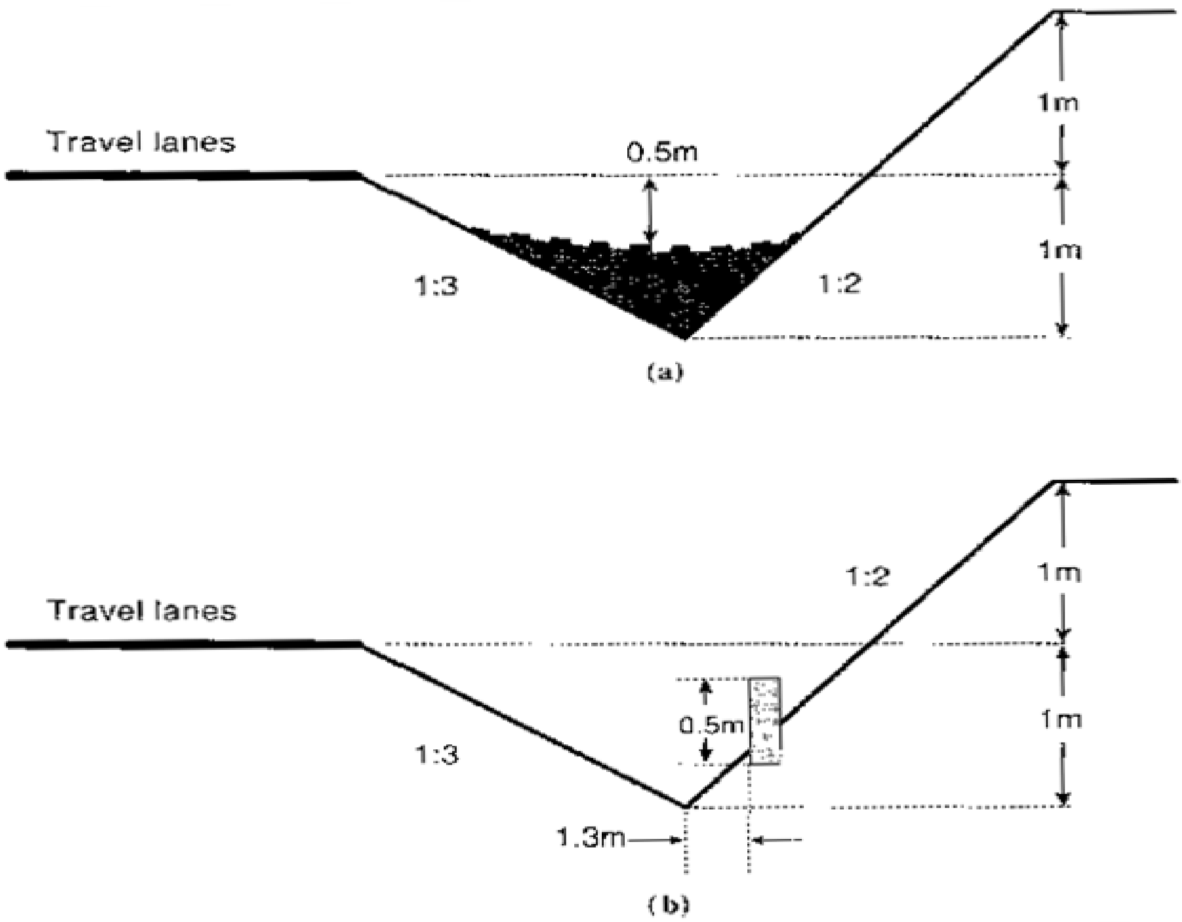

Figure 6. V-Shaped Ditch Configurations: (a) Loose Gravel and (b) Longitudinal Barrier

Table 4. Simulated Vehicle Behavior for Front Slope Traversals - Special Conditions [29]

Velocity (mph)	Encroachment Angle (degrees)	Front Slope (V:H)	Steer Back Begins (sec)	Coefficient of Friction (μ)	Surface Discontinuity Description	Maximum Roll Angle (degrees)	Remarks*
80	15	1:3	0.75	0.2/1.0	change μ	37.0	N/A
80	15	1:3	0.75	0.2/2.0	change μ	271.0	Vehicle Rolled
80	15	1:3	1.50	0.2/2.0	change μ	203.0	Vehicle Rolled
80	15	1:4	0.75	0.2/2.0	change μ	202.0	Vehicle Rolled
80	15	1:5	0.75	0.2/2.0	change μ	53.2	Vehicle Rights
60	15	1:2	0.75	0.2/2.0	change μ	190.0	Vehicle Rolled
60	15	1:3	0.75	0.2/2.0	change μ	29.3	N/A
80	15	1:3	0.75	0.2	6" curb	271.0	Vehicle Rolled
60	15	1:3	0.75	0.2	6" curb	204.0	Vehicle Rolled
60	15	1:4	0.75	0.2	6" curb	58.0	N/A
80	15	1:3	0.75	0.2	1V:2H rise on 1V:3H fill slope	-39.5	Vehicle Rolled Counter-Clockwise
60	15	1:3	0.75	0.2	1V:2H rise on 1V:3H fill slopes	-52.0	Max Roll Angle Counter-Clockwise

*No rollover occurred for any condition at 40 mph.

3.3 Parallel-Drainage Structure and Median Dike Research

In 1971, TTI researchers conducted a series of simulations on sloped culvert grates to determine safe design guidelines for parallel, sloped culvert grate structures [37-38]. Based on the original mathematical model (HVOSM) developed by Cornell Aeronautical Laboratory [25-26], TTI researchers utilized a modified version of HVOSM [30] in several roadside safety studies. For this specific study, HVOSM computer simulation was used to investigate the dynamic behavior of a 1963 Ford Galaxie as it left the traveled way and traversed a grated median culvert. A total of 23 different scenarios were simulated, all of which were characterized by the same vehicle departure speed (i.e., 60 mph) with varying departure angles. No full-scale vehicle crash tests were performed. Different combinations of median side slope and grate slope were investigated. The complete list of simulation conditions examined in this study can be found in Table 5.

Three criteria were used to examine whether the combination of slopes should be deemed safe or unsafe: (1) automobile stability; (2) automobile airborne distance; and (3) automobile acceleration severity index as developed by Hyde [31]. The simulation results led to the findings shown below.

1. For side slope to grate slope traversals, the tendency for an automobile to roll over increases as the angle of departure decreases.

2. For head on traversals of grate slopes:
    a. The acceleration severity index for a grate slope of 1V:10H indicates that an automobile's occupant could usually sustain the maneuver without serious injury.
    b. For grate slopes steeper than 1V:10H, the severity index indicates that severe injuries would probably occur.
    c. Rollover (actually pitch over) will occur for a 1V:6H slope with a ditch depth of 3 feet.

3. Rollover will occur for certain departure paths for a 1V:6H side slope used in conjunction with 1V:10H and steeper grate slopes.

4. For a 1V:6H side slope and 1V:6H grate slope, reducing the ditch depth from 3 feet to 2 feet did not prevent rollover.

In addition, the TTI simulation results indicated that a vehicle could safely traverse a terrain configuration consisting of 1V:8H median side slopes and a 1V:10H grate slope under departure angles of 25 degrees or less for speeds up to 60 mph.

In 1972, University of Michigan researchers also conducted a computer simulation effort involving vehicular impacts into sloped terrain [39]. More specifically, the simulation study investigated the safety performance of median dikes placed perpendicular to the flow of traffic using a Cornell Aeronautical Laboratory Single Vehicle Accident (CALSVA) model [25-26]. For this study, a 1963 Ford Galaxie four-door sedan was utilized throughout the duration of experiment since the majority of the vehicles on the roadway at that time fell within the same weight class (i.e. 3,820 lbs). The evaluation criteria considered the level, direction, and duration of several kinematic variables, including: incremental change in velocity, acceleration, and acceleration onset. Using existing Michigan Department of Transportation roadway standards, an 18-in. high dike with front and back slopes of 1V:6H was generated within the model. The sensitivity analysis consisted of altering the vehicle approach velocity from either 40 or 80 mph, approach angle from 0 or 25 degrees, and dike approach slope from 1V:6H or 1V:10H, one parameter at a time. Soil conditions were assumed to be very stiff or frozen for the majority of the tests, although a soft-moist condition was also considered.

Table 5. TTI Computer Simulation Results for Safe Sloping Culvert Grates [37-38]

	Terrain			Vehicle											
								Accelerations Over 50 Milliseconds							
								Grate Slope Contact				Terrain Contact After Airborne			
Run No.	Ditch Depth (ft)	Side Slope (V:H)	Grate Slope (V:H)	Approach Angle (degrees)	Maximum Roll Angle (degrees)	Rise of C.G. Above Terrain (ft)	Distance Airborne (ft)	$G_{long.}$	$G_{lat.}$	$G_{vert.}$	Severity Index	$G_{long.}$	$G_{lat.}$	$G_{vert.}$	Severity Index
1	3	1:6	1:4	25	RO	11.8	93	5.1	1.9	10.8	2.1				
2	3	1:6	1:6	25	RO	6.3	85	3.5	1.1	6.8	1.3				
3	3	1:6	1:8	25	RO	5.8	58	1.8	0.9	4.6	0.9				
4	3	1:6	1:10	25	RO	4.7	52	0.3	1.3	6.5	1.1				
5	3	1:6	1:6	25	51	6.7	86	1.1	0.6	4.4	0.8	1.3	4.8	3.9	1.0
6	2	1:6	1:6	25	RO	7.8	87	1.9	1.1	7.1	1.3	-	-	-	
7	3	1:8	1:6	25	7	8.8	101	2.8	0.4	9.1	1.7	0.3	0.7	9.7	1.6
8	3	1:8	1:6	15	34	9.9	98	2.3	0.3	6.9	1.2	2.2	2.9	4.1	0.9
9	3	N/A	1:4	0	0	18.2	147	3.6	0	8.7	1.6	1.9	0	18.4	3.1
10	3	N/A	1:6	0	0	12.2	116	1.3	0	5.3	0.9	8.4	0	7.7	2.1
11	3	N/A	1:8	0	0	7.2	98	0.6	0	3.7	0.6	4.5	0	6.6	1.4
12	3	N/A	1:10	0	0	4.7	86	0.1	0	3.1	0.5	3.0	0	5.9	1.1
13	3	1:8	1:8	5	50	6.6	82	0.2	0.4	3.6	0.8	2.9	5.4	2.7	1.1
14	3	1:8	1:8	5	RO	6.1	97	0.2	0.5	3.6	0.6				
15	3	1:8	1:8	10	40	6.4	78	0.9	0.3	4.4	0.8	2.2	0.7	2.9	0.8
16	3	1:8	1:8	15	50	6.3	68	1.2	0.4	4.4	0.8	1.9	3.2	2.0	0.7
17	3	1:8	1:8	20	21	6.2	78	1.4	0.3	6.3	1.1	1.2	1.2	2.4	0.5
18	3	1:8	1:8	25	12	6.2	81	1.5	0.3	7.1	1.2	1.1	1.0	2.4	0.5
19	3	1:8	1:10	5	50	4.8	73	0.1	0.5	3.4	0.6	2.7	4.8	2.4	1.0
20	3	1:8	1:10	10	32	5	68	0.1	0.4	3.6	0.6	1.8	2.5	2.6	0.7
21	3	1:8	1:10	15	34	4.8	62	0.7	0.3	3.5	0.6	1.7	3.0	3.3	0.8
22	3	1:8	1:10	20	17	4.8	65	0.9	0.3	5.2	0.9	0.3	0.7	4.9	0.8
23	3	1:8	1:10	25	26	4.8	63	0.9	0.3	5.4	0.9	0.3	0.6	3.6	0.6

In the most severe test condition, a simulated vehicle traveling 80 mph and head-on to the 1V:6H dike was launched over 168 in. into the air. A complete listing of trial impact conditions and a summary of kinematic results are provided in Table 6. The study findings led to the conclusion that the standard 18-in. high dike profile with a 1V:6H sloping face can lead to possible injury to unrestrained passengers at impact speeds above 40 mph, thus making it unsafe for roadside use. Further conclusions included:

1. An impact velocity of 80 mph produces about twice the passenger loading that is experienced at 40 mph.
2. Striking a 1V:10H slope reduces passenger loadings by a factor of about one-half when compared to a 1V:6H slope.
3. Soft, moist soil attenuates passenger loading on the order of 50 percent when compared with rigid terrain.
4. Approaching the dike from the road shoulder appears to be less traumatic than approaching from a flat surface.

Later in 1982, TTI researchers continued the safety investigation of slopes associated with median crossover roads, driveways, and side roads in combination with parallel, roadside drainage structures located in highway cross slopes [40-41]. The study included three phases to determine safety guidelines for this roadside hardware and features. In the first phase, the HVOSM computer program was used to simulate 68 different scenarios of vehicles traversing driveways to gain a basis for full-scale crash testing. From the simulation effort, several tentative conclusions were made:

1. Curved transitions between the ditch and driveway slopes significantly reduce the potential for rollover when the errant vehicle crosses the transition region.
2. Rollover will occur at speeds between 40 and 50 mph for ditch-to-driveway impacts when both the ditch and driveway have a 1V:4H slope and the ditch depth is in the range of 2 to 3 ft, regardless of transition type.

3. Rollover will occur at speeds between 40 and 50 mph for 1V:6H ditch and driveway slopes and ditch depths of 2 ft, regardless of transition type.

4. Rollover will occur at speeds between 50 and 60 mph for 1V:6H ditch and driveway slopes and ditch depths of 3 ft, regardless of transition type.

5. The 4,500-lb sedan did not appear to be more stable than the 2,250-lb vehicle.

The second phase of the TTI study was comprised of ten full-scale vehicle crash tests using free-wheeling, 1975 Chevrolet Vega (2,250 lbs) cars, five of which were strictly used to investigate the hazards of a driveway slope. Driveway conditions for these preliminary tests consisted of a 3-ft high earth berm with face slopes of approximately 1V:4H and 1V:7H. These test results showed that the vehicle was able to traverse the 1V:7H configuration at a speed of 50 mph or less with minimal pitching. The third phase utilized two crash tests to verify the results obtained in the previous phases. Again, the vehicle was able to traverse a 1V:7H driveway at speeds up to 50 mph with only slight damage. The HVOSM computer simulation results as well as the impact conditions and results from the 12 full-scale crash test conditions are provided in Tables 7 through 9.

From this study, the authors also concluded that an errant vehicle should be able to traverse a ditch-driveway-culvert configuration without rollover for speeds up to 50 mph as long as several conditions are met. First, the roadway side slope or ditch slope in the vicinity of the driveway slope should be 1V:6H or flatter. Second, the driveway slope should be 1V:6H or flatter. Finally, the transition area between the roadway side slope and driveway slope should be rounded or smooth rather than abrupt in order to reduce the possibility of a rollover.

Table 6. Summary of Michigan Dike Impact Conditions and Simulation Results [39]

Factors Effecting Vehicle Dynamics	Trial Specific Characteristics	Velocity (mph)	Departure Angle (degrees)	Maximum Vertical Acceleration (g)	Change in Maximum Vertical Velocity (ft/s)	Maximum Center of Gravity Height (in.)
Approach Angle						
	-	40	0	16.9	21.2	60.9
	-	40	25	9.9	34.8	50.5
Approach Velocity						
	Flat Approach Profile	40	0	16.9	21.2	60.9
	Flat Approach Profile	80	0	30.3	72.6	168.1
	Full Median Approach Profile	40	25	8.2	17.8	50.4
	Full Median Approach Profile	80	25	12.7	59.3	59.1
Lateral Impact Position						
	Lateral Position Centered	40	0	16.9	21.2	60.9
	One Wheel Flat, One on Dike	40	0	1.6	2.8	4.8
Dike Approach Slope						
	1V:6H	40	0	16.9	21.2	60.9
	1V:10H	40	0	9	10.4	33.4
Soil						
	Flat Approach Profile	40	25	9.9	34.8	50.5
	Full Median Approach Profile	40	25	8.2	17.8	50.4
Median Profile						
	Rigid Soil	40	0	16.9	21.2	60.9
	Soft, Moist Soil	40	0	4.9	13	47.6

Table 7. TTI Parallel-Drainage Structure HVOSM Simulation Results (2-ft Ditch) [40]

Run No.	Vehicle Data			Roadside Data			Simulation Results								
										Vehicle Accelerations (G's)					
										Peak			50 ms Avg.		
	Weight (lb)	Speed (mph)	Angle (deg)	Type of Transition	Driveway Slope (V:H)	Side Slope (V:H)	Maximum Roll Angle (deg)	Maximum Pitch Angle (deg)	Distance Vehicle Airborne (ft)	Long.	Lat.	Vert.	Long.	Lat.	Vert.
1	2250	30	15	Abrupt	1:6	1:6	14	16	33	2.6	2.0	4.4	1.6	1.2	2.4
2	2250	40	15	N/A	1:4	1:4	38	19	74	1.6	13.0	20.7	0.8	7.7	11.3
3	2250	40	0	N/A	1:4	1:4	0	18	77	4.6	0.0	26.9	4.6	0.0	13.4
7	2250	40	15	Abrupt	1:6	1:6	181	12	47	3.7	8.4	1.9	3.3	6.2	1.6
8	2250	40	15	Curved	1:6	1:6	53	8	53	2.5	7.2	6.6	1.8	3.6	2.5
9	2250	40	15	N/A	1:6	1:6	29	14	58	2.7	3.9	11.0	1.8	1.8	6.5
10	4500	40	15	Abrupt	1:6	1:6	32	8	43	1.7	2.8	9.3	1.3	1.6	4.9
11	4500	40	15	N/A	1:6	1:6	37	7	56	2.0	4.2	9.6	1.6	2.8	3.2
12	2250	50	15	Curved	1:4	1:4	42	31	66	7.3	6.3	5.0	4.5	3.4	2.8
13	2250	50	15	N/A	1:4	1:4	185	15	109	5.4	3.4	32.9	4.4	2.1	19.3
14	2250	50	0	N/A	1:4	1:4	0	180	111	27.4	0.0	13.1	23.3	0.0	10.5
15	2250	50	15	Curved	1:4	1:5	118	150	70	8.8	8.0	4.1	8.0	7.2	2.8
16	2250	50	15	N/A	1:4	1:5	588	70	113	4.5	64.3	11.9	2.4	19.7	6.5
17	2250	50	15	Curved	1:6	1:5	230	49	61	6.0	7.2	2.7	5.0	5.3	1.7
18	2250	50	15	N/A	1:6	1:5	182	21	88	5.9	6.4	18.5	3.4	3.0	6.3
19	2250	50	15	Abrupt	1:6	1:6	223	52	81	9.6	2.1	5.9	6.6	2.0	3.6
20	2250	50	15	Curved	1:6	1:6	40	25	71	5.5	5.4	5.0	3.6	2.6	2.7
21	2250	50	15	N/A	1:6	1:6	78	15	87	6.0	13.2	4.7	3.7	6.2	2.3
22	4500	50	15	Abrupt	1:6	1:6	42	12	56	2.6	4.5	5.6	2.0	3.4	3.1
23	4500	50	15	N/A	1:6	1:6	185	9	77	3.0	22.1	13.3	2.8	9.5	3.8
24	2250	60	15	Curved	1:4	1:4	240	60	93	11.7	4.3	6.6	8.8	3.1	4.9
25	2250	60	15	N/A	1:6	1:5	62	13	125	6.6	16.4	13.3	4.6	9.1	5.7
26	2250	60	15	Curved	1:6	1:6	29	35	75	6.3	5.4	13.8	3.5	3.4	4.3
27	2250	60	0	N/A	1:6	1:6	0	30	125	15.7	0.0	17.6	9.0	0.0	8.6
28	4500	60	15	Abrupt	1:6	1:6	68	21	73	3.3	5.6	2.8	3.3	5.6	2.7
29	4500	60	0	N/A	1:6	1:6	0	35	103	14.9	0.0	14.3	10.4	0.0	9.0

Table 8. TTI Parallel-Drainage Structure HVOSM Simulation Results (3-ft Ditch) [40]

Run No.	Vehicle Path			Roadside Data			Simulation Results								
										Vehicle Accelerations (G's)					
										Peak			50 ms Avg		
	Weight (lb)	Speed (mph)	Angle (deg)	Type of Transition	Driveway Slope (V:H)	Side Slope (V:H)	Maximum Roll Angle (deg)	Maximum Pitch Angle (deg)	Distance Vehicle Airborne (ft)	Long.	Lat.	Vert.	Long.	Lat.	Vert.
1	2250	40	15	Abrupt	1:4	1:4	17	22	62	7.3	2.9	16.5	4.9	2.0	6.8
2	2250	40	15	Curved	1:4	1:4	13	14	62	2.7	2.8	24.9	1.4	1.3	17.0
4	2250	40	0	N/A	1:4	1:4	0	17	75	6.5	0.0	31.9	3.9	0.0	9.2
7	2250	40	15	Abrupt	1:6	1:6	17	12	64	2.9	3.2	14.8	1.7	1.9	9.7
8	2250	40	15	N/A	1:6	1:6	19	14	54	2.6	2.5	10.6	1.8	1.5	6.7
9	2250	50	15	Abrupt	1:4	1:4	360	14	94	3.6	1.7	28.2	3.0	1.2	20.1
10	2250	50	15	Curved	1:4	1:4	190	24	86	5.1	3.0	27.5	4.6	1.3	18.8
12	2250	50	0	N/A	1:4	1:4	0	21	77	6.2	0.0	30.5	6.2	0.0	12.5
13	4500	50	15	Abrupt	1:4	1:4	52	22	70	2.2	11.9	7.8	1.7	8.8	4.3
14	4500	50	15	N/A	1:4	1:4	33	23	98	2.6	2.6	22.1	1.9	1.6	15.5
15	4500	50	0	N/A	1:4	1:4	0	22	98	6.7	0.1	27.0	3.7	0.1	21.4
20	2250	50	15	Abrupt	1:6	1:6	194	14	95	5.4	11.2	4.5	3.9	6.4	1.5
21	2250	50	15	Curved	1:6	1:6	11	8	87	1.5	2.8	19.6	1.0	1.5	13.1
23	2250	50	0	N/A	1:6	1:6	0	16	90	6.0	0.0	25.3	3.9	0.0	11.9
24	4500	50	15	Abrupt	1:6	1:6	54	13	76	2.5	12.1	7.1	2.0	9.4	5.4
25	4500	50	15	N/A	1:6	1:6	59	14	83	2.9	15.6	22.6	2.6	12.0	7.6
26	2250	60	15	N/A	1:4	1:4	206	22	123	6.4	16.2	10.3	6.4	11.6	3.6
27	2250	60	0	N/A	1:4	1:4	0	180	152	40.2	0.0	12.1	29.2	0.0	11.0
28	4500	60	15	Abrupt	1:4	1:4	187	8	103	2.3	24.5	11.9	2.3	16.9	9.0
29	4500	60	15	N/A	1:4	1:4	13	38	128	7.1	1.0	48.0	3.9	0.7	20.6
30	4500	60	0	N/A	1:4	1:4	0	21	143	4.0	0.0	54.0	2.0	0.0	28.9
33	2250	60	15	Abrupt	1:6	1:6	195	28	133	6.5	1.7	10.8	5.7	0.7	7.5
34	2250	60	15	Curved	1:6	1:6	47	11	121	5.0	11.0	17.7	3.4	6.9	6.4
36	2250	60	0	N/A	1:6	1:6	0	26	130	14.0	0.0	24.6	7.6	0.0	10.6
37	4500	60	15	Abrupt	1:6	1:6	192	12	105	2.1	5.2	24.6	1.9	2.6	12.2
39	4500	60	0	N/A	1:6	1:6	0	-22	124	10.2	0.0	28.9	7.1	0.0	12.3

Table 9. TTI Parallel-Drainage Structure Impact Conditions and Test Results [40-41]

Test No.	Vehicle Speed (mph)	Vehicle Path	Driveway Slope	Ditch Slope	Results
1-1	30	Head on	1V:3.8H	NA	Satisfactory, no rollover
1-2	35	Head on	1V:3.8H	NA	Satisfactory, no rollover
1-3	40	Head on	1V:3.8H	NA	Satisfactory, no rollover
1-4	50	Head on	1V:3.8H	NA	Unsatisfactory, vehicle pitched over
5-1	50	Head on	1V:6.7H	NA	Satisfactory, no rollover
7-1	50	Head on	1V:6.7H	NA	Unsatisfactory, vehicle rolled over
7-2	50	Head on	1V:6.7H	NA	Unsatisfactory, vehicle rolled over
7-4	20	Head on	1V:6.7H	NA	Satisfactory, no rollover
7-5	50	Head on	1V:6.7H	NA	Unsatisfactory, vehicle rolled over
7-6	50	Head on	1V:6.7H	NA	Satisfactory, no rollover
9-1	40	15°	1V:6.5H	1V:6.8H	Satisfactory, no rollover
9-2	50	15°	1V:6.5H	1V:6.8H	Satisfactory, no rollover

3.4 Cross-Drainage Structure Research

In 1981, TTI researchers also investigated traffic-safe end treatments for cross-drainage structures using a combination of HVOSM computer simulations and full-scale vehicle crash testing with a 1,800-lb Honda Civic and a 4,500-lb Plymouth Fury [41-42]. The first phase of the study consisted of preliminary tests to determine acceptable designs for preventing vehicles from falling into an opening with and without a small ramp. From this effort, the researchers noted that both small and large vehicles could safely traverse culverts with a clear opening width of 30 in. Also, a pipe grate system, consisting of 3-in. schedule 40 steel pipe sections spaced on 30 in. centers, provided a safe treatment for openings wider than 30 in. and installed on the face of the opening. A ramp or curb placed at the edge of the opening provided inconclusive results in terms of increasing the potential for a vehicle to clear the opening without significant snag.

Seven full-scale crash tests were then conducted on a 1V:5H side slope to determine the safety of the culvert grates on cross-drainage structures during vehicular impacts. The impact conditions included vehicle speeds of 20 and 60 mph as well as encroachment angles of 5 degrees. The crash test results are provided in Table 10. From the study, several conclusions were made. However, one relevant conclusion drawn noted that culvert ends should be configured to match the existing side slope when terminating within the clear zone. In addition, protrusions of the culvert, wingwalls, and headwalls above the terrain in excess of 3 to 4 in. should be avoided.

Table 10. TTI Cross-Drainage Structure Impact Conditions and Test Results [41-42]

Test No.	Pass/Fail	Roadside Slope	Culvert Description	Grate Description	Vehicle Impact Conditions Weight (lbs)	Speed (mph)	Angle (degrees)
2	Pass	1V:5H	30 in. diameter corrugated metal pipe	not applicable	4,500	20	5
3	Pass	1V:5H	30 in. diameter corrugated metal pipe	not applicable	1,800	20	5
4	Pass	1V:5H	trapezoidal concrete box	3 in. standard pipe grating spaced on 30 in. centers	1,800	20	5
5	Pass	1V:5H	trapezoidal concrete box	3 in. standard pipe grating spaced on 30 in. centers	4,500	20	5
6	Fail*	1V:5H	trapezoidal concrete box	3 in. standard pipe grating spaced on 30 in. centers	1,800	60	5
7	Pass	1V:5H	trapezoidal concrete box	3 in. standard pipe grating spaced on 30 in. centers	4,500	60	5

*Impact resulted in vehicle rollover

The New York State Department of Transportation conducted a study to examine the effectiveness of culvert grates when installed on slopes as steep as 1V:4H [43]. Six drive-over tests were performed on a grate installed over an opening in a roadway surface. Two full-scale crash tests were also performed on a culvert opening treated with a rebar grate system and installed on a 1V:4H slope. The crash tests included a 1,800-lb small car impacting at 60 mph and 15 degrees and a 4,500-lb sedan impacting at 60 mph and 25 degrees. From the test program, the culvert grate system, fabricated with 1-in. diameter steel rebar spaced on 12 in. centers, was shown to safely avert vehicle snag with small cars and large sedans and demonstrated acceptable safety performance. However and after safely passing over the grate, the small car rolled over as a result of the vehicle encountering a change in the embankment slope in combination with loose, wet soil. In conclusion, it was noted that the roadside terrain appeared to have more influence on vehicle trajectory than that provided by the culvert end and grate system.

Later and in 2008, the Midwest Roadside Safety Facility (MwRSF) completed a research study to investigate the safety performance of a pipe culvert grate system installed on 1V:3H fill slopes [44-45]. Researchers and State DOT personnel had expressed concern regarding the use of the culvert grate systems installed on 1V:3H fill slopes; since, the general guidance was based on results obtained from prior testing and evaluation programs which utilized 1V:5H fill slopes. Thus, two full-scale vehicle crash tests were conducted on a grate system installed on 1V:3H fill slope.

The first crash test consisted of a 4,484 lb pickup truck traversing the slope at an angle of 25.4 degrees and a speed of 60.8 mph. During the test, the vehicle was able to the completely traverse the grate system. In addition, only moderate damage was observed on both the grate system and exterior of the vehicle. All occupant risk factors were within the acceptable limits provided by National Cooperative Highway Research Program (NCHRP) Report No. 350 [46].

The second crash test consisted of a 1,997-lb small car traversing the slope at an angle of 18.7 degrees and a speed of 61.3 mph. Again, the vehicle was able to completely traverse the grate system, and all evaluation criteria were met and within the limits of NCHRP Report No. 350. From this testing program, the researchers found the standard grate system developed by TTI researchers in 1981 and adopted by AASHTO was acceptable for use on 1V:3H fill slopes.

3.5 Roadside Curb Research

Dating back to the 1950s, curbs have been tested and evaluated for safe use along high-speed roadsides. In these research programs, curbs have been tested and evaluated using vehicular impacts in both tracking and non-tracking modes as well as in combination with other roadside features, such as guardrails. However, only a limited number of computer simulation and crash testing efforts have been performed on curbs subjected to non-tracking impact conditions due to the difficulty in designing a reliable and repeatable full-scale crash test protocol.

The following sections summarize the relevant results obtained from prior computer simulation and crash testing studies involving roadside curbs as well as their effect on vehicle trajectory and stability.

3.5.1 Tracking Impacts

Two initial studies involving tracking impacts with curbs were conducted in the mid 1950’s by Beaton and Fields at the California Division of Highways [47-48]. The purpose of these studies was to evaluate the dynamic performance of bridge curbs and rails during full-scale crash testing. The first phase of testing was conducted in 1953 and consisted of numerous crash tests on eleven different curb configurations using a 1949 Ford sedan weighing 3,224 lbs. The eleven curb configurations examined were comprised of vertical, sloping, and undercut faces with heights of 6 in., 9 in. and 12 in. The test results showed the affect that curb geometry had in vehicle redirection and warranted more tests to evaluate the effect of curb height on vehicle trajectory.

The second phase of testing was conducted in 1955 to further investigate the dynamic effect curb height had on vehicle trajectory during collision. The four most promising curb configurations, as established in the 1953 findings, were modified to include 9 in., 10 in., 11 in., and 12 in. variations. The primary focus in these tests was to provide specific recommendations for the design of efficient barrier curbs. Four sedans, similar to the one used in the 1953 study, were employed for testing. Tests were conducted at impact angles of 7½, 15, 20, and 30 degrees and at impact speeds of 10, 15, 20, 30, 40, 45, 50, and 60 mph. The test results indicated that the curb's effectiveness to behave as a barrier under vehicular impacts varied directly with curb height and inversely with the angle of collision. Further, the magnitude of a vehicle's "dynamic jump" (i.e., vertical trajectory) increased with an increase in curb height. Therefore, the most efficient barrier curb height was deemed to be 10 in. However, the researchers indicated that vehicular impacts with barrier curbs could possibly cause the driver to lose control of the vehicle.

In 1974, TTI researchers introduced refined safety design guidelines for tracking impacts with curbs [49]. In the study, three common AASHTO curb configurations (B, D and G) were investigated along with an experimental curb (X) to evaluate how different curb types affected vehicle stability. In particular, vehicle path (trajectory), vehicle attitude (overall behavior) and vehicle accelerations (severity of impact) were examined. Computer simulations and full-scale crash tests were collectively used in the study. A 1963 Ford Galaxie was used in each of the 18 full-scale crash tests involving curb types B and D and modeled in each of the 48 HVOSM computer simulations involving curb types B, D, G and X. Impact conditions for the computer simulations included speeds of 30, 45, 60, and 75 mph and angles of 5, 10, 12.5, 15, and 20 degrees. Impact conditions for the full-scale crash tests included speeds of 30, 45, and 60 mph and angles of 5, 12.5, and 20 degrees. The research team determined that the simulation results, as shown in Table 11, correlated well with the full-scale crash testing results. The key conclusion drawn from this study was that curbs should not be placed along high-speed highways. Further, even though a lower speed impact (i.e., 30 mph and 5 degrees) was described as redirective in the report, it should be noted that a plot of the vehicle's trajectory actually illustrated curb override. Thus, these curb configurations should not be implemented as a barrier device along low-speed roadways. Further conclusions were identified and are listed below.

1. Curbs 6-in. high or less with configurations similar to that used in the experiment will not redirect a vehicle at speeds greater than 45 mph and impact angles greater than 5 degrees. Since vehicles travel at higher speeds on most rural highways, these curbs should not be used as a type of redirection hardware.

2. High speed curb impacts can cause vehicle ramping and have the capability to damage the steering mechanism of a vehicle, making these devices a potential hazard rather than enhancement if placed along the roadside.

3. Vehicle impacts with curbs 6 in. or less will result in minor to no injuries, since vehicles can traverse such configurations with ease and slight divergence from the initial encroachment path.

In 1994, MwRSF researchers conducted a study involving vehicular impacts with mountable curbs [50]. Three frequently employed Nebraska Department of Roads (NDOR) curb designs were used: one 6-in. high curb with a 1V:3H sloping face; one 4-in. high curb with a 1V:3H sloping face; and one 6-in. high AASHTO type I curb. Full-scale vehicle crash testing and HVOSM computer simulations were used to evaluate impact performance in terms of the following criteria: vehicular trajectory; roll; pitch; yaw angular displacements; and bumper trajectory.

The crash testing program consisted of 23 tests conducted with 1,800-lb and 4,500-lb free-wheeling vehicles traveling at impact speeds of 40, 45, 50, and 55 mph and approach angles of 5, 12.5, and 20 degrees. The maximum observed roll and pitch angles for high-angle impacts was 9.7 and 3.1 degrees, respectively, which corresponded to testing with an 1,800-lb vehicle on the AASHTO type I curb.

Table 11. TTI Curb Study - Selected Simulation Conditions and Results [49]

Curb Type	Vehicle Speed (mph)	Impact Angle (deg)	Maximum Roll Angle (deg)	Maximum Pitch Angle (deg)	Maximum Bumper Height Above Curb (in.)	Lateral Distance to Max Rise Point (ft)	Peak Accelerations Averaged Over 2 Milliseconds[b] (g's) Long.	Lat.	Vert.
E (6 in.)	30	5	-10.2	2	–[a]	–[a]	0.1	0.5	0.5
	30	12.5	-9.5	2	21	4	0.2	1.0	1.5
	30	20	-8	2.5	21	6	0.6	2.0	3.3
	45	5	-11	2	–[a]	–[a]	0.1	0.6	0.9
	45	12.5	-11	2	23	5	0.5	2.2	3.8
	45	20	-8	2.2	25	8	1.0	2.9	5.9
	60	5	-11.2	2	23	3	0.1	0.8	1.8
	60	12.5	-12	2	25	6	0.7	3.3	6.3
	60	20	-9.5	2.5	31	10	1.3	4.1	9.2
	75	5	-12	1.5	23	4	0.1	1.2	2.3
	75	12.5	-13	2	25	6	0.6	3.4	6.5
	75	20	-11	2	31	9	1.2	4.4	10.2
X (13 in.)	30	5	-4	1	–[a]	–[a]	0.3	1.6	1.3
	30	12.5	-8	7	–[a]	–[a]	1.1	5.1	5.1
	30	20	-16	10	–[a]	–[a]	2.6	7.9	8.0
	45	5	3	3	–[a]	–[a]	0.5	2.9	2.8
	45	12.5	-28	9	–[a]	–[a]	1.7	8.4	9.1
	45	20	-25	9	53	5	2.7	9.5	17.6
	60	5	-2	3	–[a]	–[a]	0.3	5.2	1.5
	60	12.5	-48	9	–[a]	–[a]	3.1	11.2	14.2
	60	20	-30	8	63	8	3.2	9.1	26.2
	75	5	-8	3	–[a]	–[a]	0.4	5.1	5.4
	75	12.5	-51	9	–[a]	–[a]	1.8	11.4	15.0
	75[c]	20	-180	7	85	9	2.4	9.3	25.1

[a] Curb was not crossed, vehicle was redirected
[b] The peak acceleration components may not occur simultaneously
[c] Rollover

The vehicle's driver in that test also reported that the suspension system had completely bottomed out during impact. However, the wheels of the vehicle remained in contact with the pavement at all times during and after the impact so vehicle stability was not compromised. The results from the full-scale crash tests were used to validate the HVOSM models for each of the original 23 scenarios. An additional 55 simulations were also performed to investigate alternative impact scenarios.

For each curb type examined, the measured vehicle deceleration, roll angle, and pitch angle were found to be very low. Further, the resulting vehicle damage was minimal. Therefore, it was concluded that tracking impacts with these curb configurations did not pose a significant hazard to vehicles or the interior occupants.

In 2002, Worcester Polytechnic Institute (WPI) researchers conducted a study to investigate pickup truck impacts with curbs and curb-guardrail combinations [51-52]. Project funding was allocated for this study since much of the prior research had primarily focused on sedan impacts with curbs. For this study, computer simulations were performed using the LS-DYNA computer software [53]. The NCAC C2500R pickup truck model, weighing approximately (4,409 lbs) [54-55], was used for the study. Validation for the various components used in each model (e.g., vehicle, guardrail, etc.) was obtained by comparing numerical results to those obtained from an extensive literature review on documented full-scale crash test results. In the study, six different curb designs were examined: a 6-in. high AASHTO Type A curb; a 6-in. high AASHTO Type B curb; a 4-in. high AASHTO Type C curb; a 6-in. high AASHTO Type D curb, a 4-in. high AASHTO Type G curb, and a 4-in. high New York configuration. The impact conditions for the computer simulations consisted of speeds of 43.5 and 62.1 mph and angles of 5, 15, and 25 degrees.

The WPI researchers later concluded that pickup truck impacts with these curb types (i.e., no barrier combination) did not compromise the vehicle stability during tracking impacts. Further, the vehicle's speed and angle as well as the slope of the curb face had little influence on the vehicle's trajectory. However, the most significant factor effecting vehicle trajectory was determined to be curb height. Furthermore, an examination of Acceleration Severity Index (ASI) values demonstrated that a lower height curb with a milder face slope was much less likely to cause a driver to lose control of the vehicle. Loss of vehicular control was categorized with only the most extreme impact cases.

3.5.2 Non-Tracking Impacts

In 1990, engineers at Failure Analysis Associates, Inc. (FaAA) performed a study to determine methods for accurately predicting vehicle rollover [56]. Three full-scale mechanisms were used to test and evaluate vehicle behavior in a tripped situation: (1) sliding into a curb; (2) sliding in soil; and (3) rolling off of a dolly. A total of eight full-scale tests were performed in the study: five into curbs; two into soil; and one with a dolly apparatus. Four different vehicle types were utilized, including a 1981 Dodge Challenger, a 1979 Datsun B210, a 1972 Chevrolet C20 Van, and a 1981 Chevrolet Impala.

The five curb trip tests were conducted by using a tensioned wire to tow a vehicle sideways along a stretch of pavement into a 6-in. high square steel tube in order to represent a curb. The test vehicles were propelled at a nominal speed of 30 mph for these curb impacts. The curb was placed perpendicular to the path of the vehicle. In order to perform a consistent test, the researchers reduced tire-pavement friction on the roadway by coating it with a soapy film. To compensate for this lack of tire-pavement interaction, the vehicle was given an initial roll angle of 2.5 degrees. This condition was accomplished by extending one side of the vehicle's suspension system and holding it with wood shim blocks.

For the two soil trip tests, a section of roadway along the vehicle path was removed, excavated, and replaced with a 12-in. thick layer of a loosely-packed mixture of dirt and finely crushed granite. The soil test section was 40 ft long by 20 ft wide. The single dolly trip test was performed with the vehicle initially inclined to a 23-degree roll angle prior to being released and with the leading tires raised 9 in. above the ground. For these three tests, the vehicle was again oriented in a perpendicular path (non-tracking) and utilized the nominal test speed of 30 mph.

Two out of the five curb trip tests resulted in vehicle rollover, while each of the soil trip and dolly trip tests resulted in vehicle rollovers. Average decelerations experienced during the curb trip test exceeded 10 G's, while average decelerations experienced during the soil trip tests ranged between 1.5 to 2.0 G's. The higher decelerations associated with curb trip were attributed to shorter sustained tripping forces as compared to the soil trip tests. Failure to rollover in the remaining three curb trip tests was attributed to excessive damage sustained by the vehicle's wheels and axles during impact. The collapse of these components reduced the duration of peak loading on the vehicle, thus causing an insufficient impulse to produce rollover. Further testing conditions and results are shown in Table 12.

The results from these tests were used to create an analytical model to predict the impulse required to trip a vehicle based on the assumption of a constant tripping force. The model compared well with the test results. However, the researchers concluded that the kinematics of a tripped vehicle varied significantly depending on the tripping mechanism.

Table 12. FaAA Curb Tripping Study [56]

Test No.	Vehicle Type	Vehicle Weight (lbs)	Vehicle C.G. Height (in.)	Test Speed (mph)	Trip Method	Average Deceleration During Trip Phase (G's)	Peak Angular Velocity (degrees/sec)	Test Result
1	1981 Dodge Challenger	2964	20.9	29.9	Curb	6.00	-	no rollover
2	1981 Dodge Challenger	2964	20.9	29.6	Curb	12.40	260.00	rollover
3	1979 Datsun B210	2263	20.3	29.3	Curb	13.20	300.00	rollover
4	1972 Chevrolet C20 Van	4690	30.3	29.6	Curb	5.50	-	no rollover
5	1981 Chevrolet Impala	3820	21.7	30.2	Curb	5.40	-	no rollover
6	1981 Dodge Challenger	2964	20.9	30.2	Dolly	1.30	460.00	rollover
7	1981 Dodge Challenger	2964	20.9	33.7	Soil	1.62	230.00	rollover
8	1979 Datsun B210	2263	20.3	27.0	Soil	1.71	390.00	rollover

In 1998, FaAA engineers further refined the results from the previous study to determine the influence of trip speed on vehicle rollover as well as establish a minimum trip speed [57]. Six full-scale tests were conducted on a 1984 Oldsmobile Cutlass Ciera weighing 3,305 lbs and using impact speeds of 13.5, 19.3, 19.8, 21.2, 23.0, and 42.9 mph. Soil trip was the only tripping mechanism considered for this series of tests. The same general test procedures employed in the 1990 study were also used for this follow-on study, with the exception that a monorail and cable system was used to guide and tow the test vehicles. This revised test protocol allowed for controlled vehicle yaw prior to trip.

The results from these six tests illustrated that vehicle trip was directly dependent upon vehicle speed. The vehicle did not rollover at the four lowest test speeds, but the vehicle did rollover at 23.0 and 42.9 mph within this study. The lowest rollover speed was 23.0 mph, while the highest non-rollover speed was 21.2 mph, thus putting the minimum soil trip speed for this mid-sized sedan between 22 and 23 mph.

In 1994, MwRSF researchers conducted non-validated, HVOSM computer simulations to investigate non-tracking impacts with the three NDOR mountable curb designs, as previously described herein [50]. Three different impact conditions were examined through a total of 18 simulation. Models of 1,800-lb and 4,500-lb vehicles traveling at 50 mph and a center of gravity trajectory angle of 20 degrees were used in each simulation, respectively. The first impact condition consisted of a 150-degree yaw angle relative to the direction of travel and a 50-degree/second yaw rate. The second impact condition consisted of a negative 30-degree yaw angle relative to the direction of travel and a negative 25-degree/second yaw rate. The last impact condition consisted of a 180-degree yaw angle relative to the direction of travel and a 50-degree/second yaw rate.

For each of the conditions described above, no vehicle rollover occurred, and the computer simulations only predicted tire blowout situations in 4 out of 18 of the cases. All 4 blowouts (left rear tire) occurred at the 6-in. curb and 180-degree yaw condition. Maximum angular displacements were relatively small. In conclusion, the study results illustrated that the noted mountable curb configurations were traversable over a wide array of vehicle orientations and impact conditions. In addition, this research demonstrated that sloping curbs may not be a significant cause of vehicle rollovers, even on high-speed facilities, and may provide adequate safety performance for all impact conditions and all highways.

3.6 Roadside Safety Design - Small Vehicle Simulation and Testing

In the early 1980s, roadside safety researchers and experts had growing concerns that the results from the previously mentioned research studies may have become relatively obsolete when considering the technological advancements of the automotive industry over the last half century. For example and in the 1970s, the geometry of the passenger vehicle fleet was becoming increasingly different than that observed in the four prior decades. Passenger vehicles were becoming smaller and lighter, some weighing 1,800 lbs or less.

Further, there was a growing awareness that these smaller vehicles could more easily overturn when traversing or impacting surface irregularities. In addition, there were concerns that the AASHTO standards regarding the safety performance of roadside hardware and features were inadequate for cars weighing 1,800 lbs or less.

In view of these concerns, the National Highway Cooperative Research Program (NCHRP) sponsored a research study at the Texas Transportation Institute (TTI) to investigate small car performance in combination with numerous roadside safety features, including slopes, ditches, driveways, and curbs [58-59]. For this study, TTI researchers examined small car performance with various features using computer simulation and full-scale crash testing and published the results in Report No. 318. In this effort, it was concluded that the consequences of a minicar traversing a slope, ditch, driveway, or curb, were not significantly different than that of a large car as long as the feature was smooth and well-compacted. However, it was repeatedly noted that small cars are more prone to overturn when surface irregularities, such as small rocks or boulders, are encountered. Specific conditions for the computer simulation and crash testing efforts are described in the following sections.

3.6.1 Fill and Cut Slopes

HVOSM computer simulation was utilized to investigate certain aspects of roadside fill and cut slopes. Models were created to represent four different minicar types (Daihatsu Domino, Chevrolet Sprint, Fiat Uno, and a Ford Fiesta) leaving the traveled way in a free-wheeling manner at a speed of 60 mph and an angle of 15 degrees. At a specified time, a steer input was initiated to simulate a return to road maneuver. Fill slopes of 6H:1V, 4H:1V and 3H:1V in combination with fill heights of 5 ft, 10 ft and 20 ft were examined. Cut slopes of 3H:1V, 2H:1V, and 1H:1V were also examined. The embankments were assumed to be composed of dry soil with a coefficient of friction of 0.5.

The results from the fill slope simulations illustrated that overturn was not predicted for any of the noted cases, but vehicle sideslip and spin out were common occurrences. Conversely, rollover was predicted for 2H:1V or steeper cut slopes.

A limited number of non-tracking encroachment simulations were also conducted. In those simulations, the vehicle was given a 15-deg/sec yaw rate as it left the roadway at 15 degrees. Both 3H:1V cut and fill slopes were examined, neither of which produced vehicle rollover.

3.6.2 Ditches

HVOSM computer simulation was again used to investigate certain aspects of roadside ditches. Models were created with the same vehicle types and encroachment conditions as utilized for the slope traversal simulations. Both tracking and non-tracking departures were examined for combinations of foreslope and backslope grades of 6H:1V, 4H:1V, and 3H:1V and with depths of 5 ft and 10 ft. The embankments were assumed to be composed of dry soil with a coefficient of friction of 0.5.

The results from the ditch simulations did not predict a propensity for vehicle overturn, but the car routinely experienced sideslip or spin out during traversal.

3.6.3 Driveways

HVOSM computer simulation and two full-scale crash tests were employed to investigate certain aspects of median driveways. Three of the four minicar types were examined for encroachment speeds of 60 mph and either head on or 15 degree orientations. Tests and simulations were conducted with a free-wheeling vehicle.

Results from the simulations and tests demonstrated that a foreslope of 6H:1V or flatter in combinations with a 10H:1V or flatter driveway slope was necessary to avoid overturn.

3.6.4 Curbs

HVOSM computer simulation and a series of full-scale crash tests were employed to investigate the safety performance of a 6-in. high, AASHTO Type B curb. Three of the four minicar types were utilized in combination with encroachment speeds greater than 40 mph and encroachment angles equal to or greater than 15 degrees.

For this effort, the study results illustrated that a minicar could traverse a 6-in. high curb with little to no alterations to its trajectory when impacted in a tracking, non-skidding condition. However, non-tracking, small car impacts will overturn more easily than a larger car. Thus, the face of curbs should be sloped as flat as possible in order to minimize overturn accidents involving non-tracking minicars.

3.7 Discussion

As previously noted, very little to no safety research has been performed to determine the crashworthiness of rock check dams and/or rock ditch liners when configured for use near the traveled way and within the roadside clear zone. As such, a literature review was performed to determine whether prior safety research pertaining to other drainage features may provide insight into the safety performance of check dams and ditch liners as well as assist with the development of preliminary design guidelines for these specific drainage features.

Following this review, the research team determined that significant safety research was performed on roadside slopes, ditches, curbs, crossover driveways, etc. which should provide relevant information for developing safety guidelines regarding the roadside use of rock check dams and ditch liners. Therefore, the findings and conclusions drawn for these common drainage structures may contain important information regarding the safety performance of other erosion control features.

Roadside slopes and ditches are commonly found along the highways and roadways. Prior studies have shown that slopes and ditches should be relatively smooth and free of obstructions in order to reduce the potential of vehicle rollover. In addition, it is widely known that vehicles traversing slopes with surface irregularities can be devastating and result in rollover. As such, prior research would dictate that slopes and ditches that are lined with rock ditch should be configured with the stones placed in a uniform manner to create the best possible, smooth and level surface.

Rock ditch liners are also similar in nature to roadside drainage curbs in the sense that portions of the rock liner may protrude above the general plane of the side slope or ditch surface.

These protrusions may essentially behave like a series of randomly-placed, short rigid curbs which could degrade vehicle stability over time. This is especially the case with the 6-in. high, blunt faced concrete header used in the California rock blanket.

Driveways and crossover roads may be very similar to rock check dams in terms of their effect on impacting vehicles. Prior safety research pertaining to driveways as well as parallel drainage structures has demonstrated that approach slopes should be 6H:1V or flatter in order to provide for safe vehicle traversals. Unfortunately, many of the surveyed State DOTs have rock check dam configurations which utilize approach slopes steeper than 6H:1V. Rock check dams with approach slopes steeper than 6H:1V may likely cause vehicle rollover at high speeds [40, 41].

Although prior research can be used to determine how a vehicle may initially respond during such impact scenarios, there are major limitations. It is obvious that initial impact with any obstruction on the roadside will increase the hazard of a secondary impact due to an altered vehicle trajectory. However, the extent of this altered vehicle trajectory and attitude is currently unknown. States will not be able to conform to one standardized set of safety practices regarding the implementation of these devices in the clear zone until full-scale testing combined with computer simulations are performed according to recommended safety performance guidelines.

4 PRELIMINARY DESIGN AND PLACEMENT GUIDELINES

4.1 Phase I Objective and Plan

Following a review of several State DOT standards, policies, and procedures, various AASHTO design guidelines, as well as numerous research studies, the research team began preparation of preliminary guidelines regarding the safe design and placement of rock check dams and rock ditch liners placed near the traveled way and within the roadside clear zone. These preliminary design and placement guidelines were to be based on computer simulations and crash tests previously performed on similar roadside safety features, utilize common material specifications, as well as consider existing construction methods and installation practices. As such, the Phase I preliminary design and placement guidelines presented herein should provide improved safety for rock check dams and rock ditch liners over that provided by the current standards, practices, and policies. However, these Phase I preliminary guidelines should be evaluated in a future phases using a combination of computer simulation and full-scale vehicle crash testing. Furthermore, these Phase I preliminary guidelines are only intended for use when rock check dams and rock ditch liners are placed within the roadside clear zone.

4.2 Rock Check Dams

From the State DOTs standards, policies, and procedures, several characteristics of rock check dams were identified that strictly corresponded to the hydraulic design and performance of the ditch and were deemed unnecessary to alter. These characteristics are as follows:

1. A rock check dam shall be entrenched 6 in. into the ditch bottom to ensure stability of the structure and create the smoothest possible transfer from soil to rock.

2. The highest point of a rock check dam should be at least 1 ft below the top of the ditch to prevent overflow onto the roadway.

3. The sides of a rock check dam shall be at least 6 in. higher than the center of the dam, thus creating a weir effect.

From the limited State DOT survey, it was discovered that a majority of check dams were being constructed using maximum rock sizes which ranged from 5 to 12 in. as shown in Table 1. It was estimated that 5-in. diameter rocks may protrude approximately 3 in. above adjacent rocks, while 12-in. diameter rocks may protrude as much as 8 in. above adjacent rocks. It is the research team's opinion that vehicular impacts with large rocks as compared to small rocks would pose increased risk to motorists. There are safety concerns regarding excessive rock exposure above the general plane of a check dam. First, a vehicle which impacts a large, exposed rock could lead to increased vehicle launch heights over and distances beyond the dam structure. Second, large exposed rocks could also result in increased propensity for vehicular instabilities while traversing the structure and/or when re-contacting the downstream side of the dam or surrounding ditch surfaces. As such, it would seem reasonable and practical to construct the top half of a check dam with rocks having a maximum size ranging from 4 to 8 in.

Further, several State DOTs were found to utilize an interesting method for lining the approach slope or face of the check dam with smaller rocks or gravel. The smaller rocks or gravel not only create a natural filter for sediment flowing through the channel, but they also provide a smoother terrain for impacting vehicles which traverse the dam structure. Therefore, consideration should be given for lining the approach slope or face of the check dam with a thin layer, say 4 to 6 in., of small rocks or gravel with sizes no larger than 1 to 2 in.

Other check dam characteristics were believed to affect vehicle stability during impacts. These structure characteristics include (a) the side slopes of ditch and the approach slope or face of the check dam and (b) the overall height of the check dam itself. From the State DOT survey, large variances were observed within these two categories. Preliminary guidelines for these two categories are listed below:

1. To minimize the size of the hazard and in turn decrease the vehicle trajectory resulting from potential collisions with the dam, a check dam should be constructed with a 2 ft maximum height along high-speed roadways, as taken from the bottom of the ditch to the bottom of the dam's weir. For roadways with greatly reduced speeds, a maximum height of 3 ft may be used but is generally not recommended.

2. For all highway speeds, check dams shall be constructed with a 1V:6H or flatter approach slope or face. However, it is recommended that check dams found along high-speed roadways utilize 1V:10H or flatter approach slope or face. For very low-speed, low-volume roadways, consideration may be given for constructing check dams with an approach slope of 1V:4H or flatter. If either the upstream or downstream side of the check dam structure is not exposed to oncoming traffic, a 1V:2H or flatter approach slope may be utilized to reduce material costs for the structure.

3. Ditch side slopes should not be steeper than the corresponding approach slope of the check dam. Rounding should be utilized at the ditch corners as well as between the ditch and check dam in order to provide smooth transitions.

A summary of the previously mentioned recommendations for various speeds along with a detailed sketch of a suggested design can be found in Table 13 and Figure 7, respectively.

Table 13. Preliminary Design Guidelines – Rock Check Dam

Design Speed (mph)	Maximum Approach Slope (V:H)	Maximum Ditch Side Slope (V:H)	Maximum Center Height (ft)
30	1:4 or flatter	1:4 or flatter	3
45	1:6 or flatter	1:6 or flatter	3
60	1:6 or flatter	1:6 or flatter	2

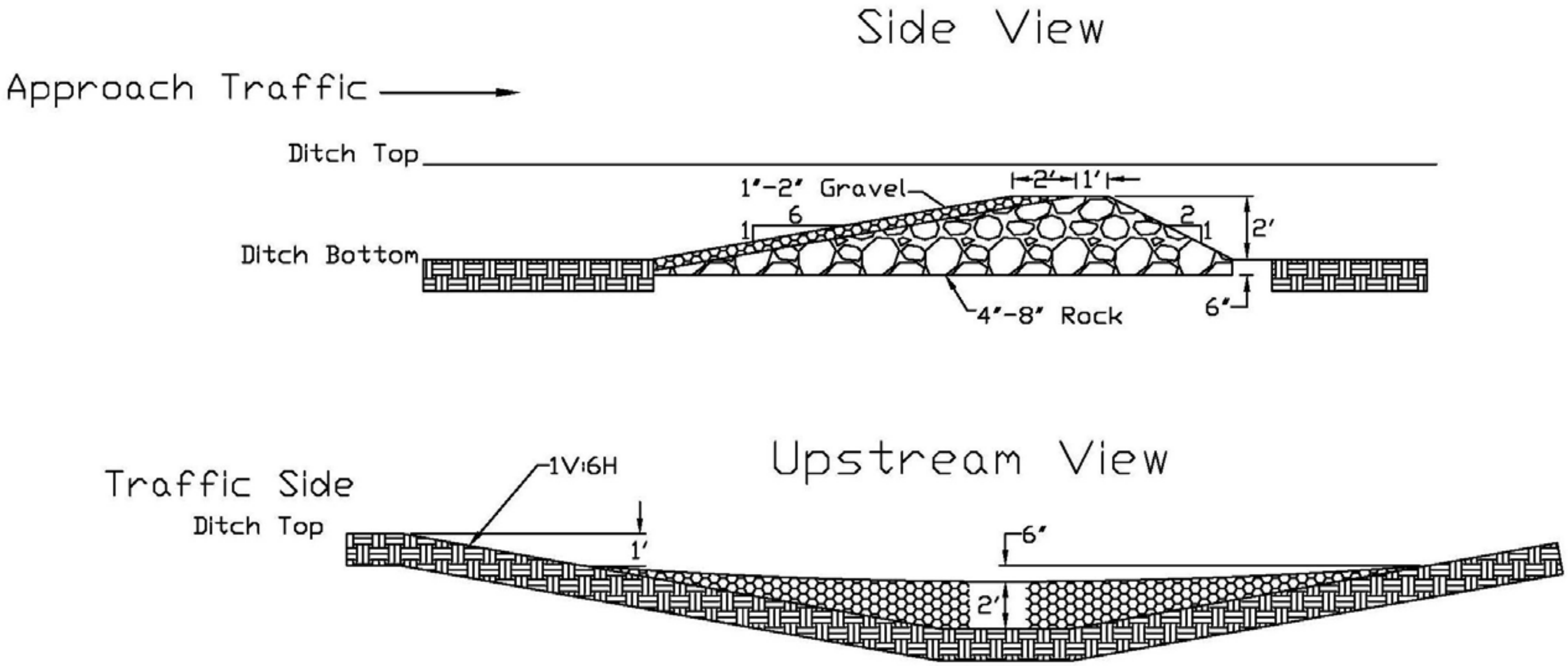

Figure 7. Preliminary Design Guideline - Rock Check Dam Schematic

4.2.1 Safety Considerations

The Phase I preliminary design and placement guidelines for check dams were based on the assumption that a relatively-stable vehicle initially strikes a smooth ditch side slope, ditch bottom, or approach slope of a single, completely rigid rock check dam. However, it is known that tracking vehicles which leave the roadway and traverse over sloped roadside terrain can exhibit moderate roll and/or pitch angles prior to re-contacting a side slope or ditch bottom. These initial vehicle motions could further degrade vehicular stability during subsequent impacts with a single rock check dam, or even sequentially-placed rock check dams, as instability concerns are magnified when a vehicle becomes airborne. Additionally, there lies the possibility for an unstable vehicle to dig into a check dam rather than smoothly traverse it, which could further degrade vehicular stability during impact.

From prior research studies involving sloped terrain and other drainage features, it was understood that several design parameters for rock check dams (i.e., center dam height, distance between consecutive dams, rock size, approach slope, etc.) could greatly influence vehicle stability both during impact as well as during traversal. Further, rock check dams are often placed sequentially along a ditch bottom to control hydraulic water flow and reduce erosion. As such, there exists the propensity for an errant vehicle to strike multiple check dams, thus potentially resulting in further degraded vehicular stability.

In fact, an errant vehicle that is traveling parallel with the ditch bottom, as depicted by Path 1 of Figure 8, would impact a single rock check dam in a head-on orientation. In addition, a vehicle trajectory resulting from such an impact could potentially result in a secondary impact with a closely-positioned, downstream check dam.

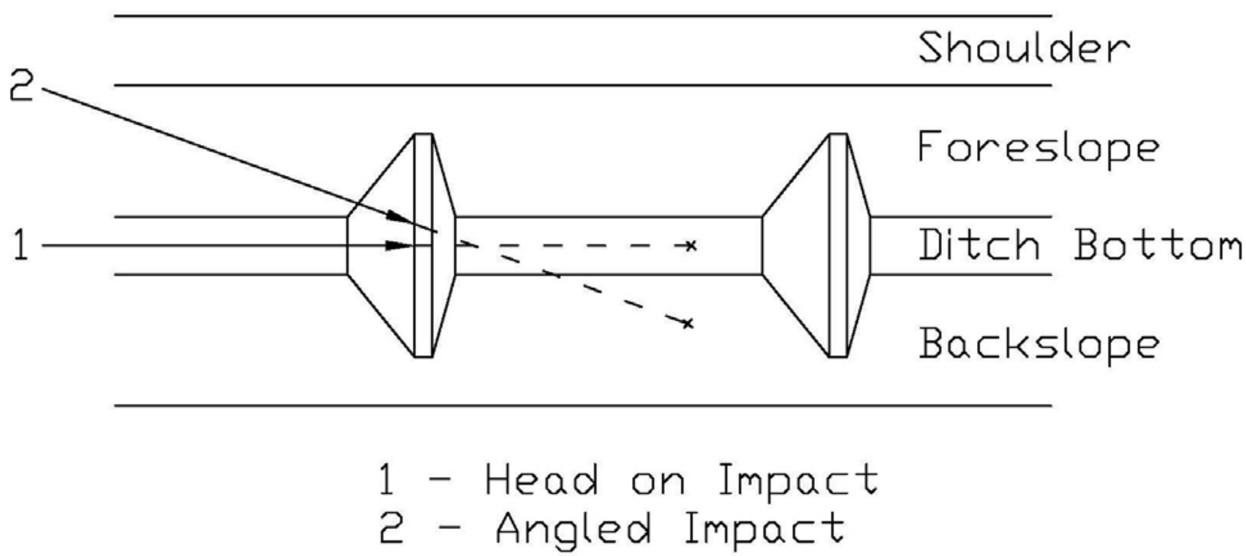

Figure 8. Typical Impact Scenarios - Rock Check Dam

Subsequently, simple particle dynamics was utilized to determine various vehicle trajectories as a function of approach slope or launch angle, ditch height, and vehicle velocity. The general physics equations shown below were utilized to perform the trajectory analysis. Equation 1 was used to determine the predicted airborne time, $t_{airborne}$, for a vehicle (particle) impacting a check dam of a given height, a given approach slope, and while traveling at a given speed. Using the calculated airborne time found with Equation 1, Equation 2 was used to determine the predicted longitudinal or horizontal airborne distance, $x_{horizontal}$, for a vehicle (particle) launched off of a check dam with varying dam heights, different approach slopes, and impact speeds. Finally, Equation 3 was used to determine the maximum height, y_{max}, reached by a vehicle (particle) above the ditch bottom when launched from a check dam of a given height, approach slope, and while traveling at a given speed.

$$t_{airborne} = \frac{v_y}{g} + \sqrt{\frac{v_y^2}{g^2} + \frac{2y_0}{g}} \tag{1}$$

$$x_{horizontal} = v_x \times t_{airborne} \tag{2}$$

$$y_{max} = \frac{v_y^2}{2g} + y_0 \tag{3}$$

Where:

v_y = vertical component of initial velocity
v_x = horizontal component of initial velocity
g = acceleration due to gravity
y_0 = height of check dam above ditch bottom

For specific combinations of approach slope, check dam height, and impact speed, Equations 1 through 3 were utilized to estimate the maximum travel height and longitudinal distance of a vehicle (particle). The analytical results are shown in Table 14 along with selected computer simulation results from a 1982 TTI research study on parallel drainage structures [40].

Table 14. Particle Trajectory Analysis with Comparison to TTI Simulations (Where Available)

Ramp Geometry		Particle Velocity			3-ft Ramp Height				2-ft Ramp Height			
						Horizontal Distance				Horizontal Distance		
Approach Slope (V:H)	Launch Angle (degrees)	Resultant Approach Speed (mph)	Horizontal Component (fps)	Vertical Component (fps)	(Eq. 1) Time Airborne (sec)	(Eq. 2) Airborne Distance[1] (ft)	TTI Simulation Results [2,250 lb] (ft)	(Eq. 3) Maximum Particle Height[2] (ft)	(Eq. 1) Time Airborne (sec)	(Eq. 2) Airborne Distance[1] (ft)	TTI Simulation Results [2250 lb] (ft)	(Eq. 3) Maximum Particle Height[2] (ft)
1:2	26.57	30	39.4	19.7	1.36	53	-	9.0	1.32	52	-	8.0
		45	59.0	29.5	1.93	114	-	16.5	1.90	112	-	15.5
		60	78.7	39.3	2.52	198	-	27.0	2.49	196	-	26.0
1:3	18.43	30	41.7	13.9	1.04	44	-	6.0	0.99	41	-	5.0
		45	62.6	20.9	1.43	89	-	9.8	1.39	87	-	8.8
		60	83.5	27.8	1.83	153	-	15.0	1.80	150	-	14.0
1:4	14.04	30	42.7	10.7	0.88	37	-	4.8	0.82	35	-	3.8
		40	56.9	14.2	1.06	60	75	6.1	1.01	57	77	5.1
		45	64.0	16.0	1.16	74	-	7.0	1.11	71	-	6.0
		50	71.1	17.8	1.25	89	77	7.9	1.21	86	111[3]	6.9
		60	85.4	21.3	1.45	124	152[3]	10.1	1.41	121	-	9.1
1:6	9.46	30	43.4	7.2	0.71	31	-	3.8	0.64	28	-	2.8
		40	57.9	9.6	0.82	48	-	4.4	0.76	44	-	3.4
		45	65.1	10.8	0.88	58	-	4.8	0.82	54	-	3.8
		50	72.3	12.0	0.95	68	90	5.3	0.89	64	-	4.3
		60	86.8	14.5	1.07	93	130	6.2	1.02	89	125	5.2
1:10	5.71	30	43.8	4.4	0.59	26	-	3.3	0.51	22	-	2.3
		45	65.7	6.6	0.68	45	-	3.7	0.61	40	-	2.7
		60	87.6	8.8	0.78	68	-	4.2	0.72	63	-	3.2

[1] – Based on flat ditch (i.e., no grade) assumption

[2] – Calculation includes initial dam height

[3] – Resulted in vehicle pitch over

These results were used to further examine potential concerns for increased vehicular instabilities resulting from an airborne vehicle and subsequent impacts with sequentially-placed, rock check dams.

Several assumptions were made when determining the vehicle (particle) trajectories with Equations 1 through 3. First, the initial approach speed was assumed to be orientated parallel to the approach slope or face of the check dam. Second, the effects of air drag on the vehicle (particle) were neglected. If air drag was included, the resulting trajectory would likely be less pronounced. Finally, the ditch grade was assumed to be level since typical changes in rise to run are relatively small (i.e., 6 percent maximum grade).

From the tabulated results, the horizontal airborne distances were aggressively used to determine a minimum check dam spacing, although no consideration was given to a vehicle recovering to a reasonably stable condition. Obviously, a check dam should not be placed within the estimated horizontal airborne distance. Ensuring no check dam is placed within this distance would prevent a vehicle traveling at or below the design speed of the roadway from launching directly onto another check dam rather than the flat ditch bottom. However, such spacing would not avert a second impact with the next downstream check dam nor ensure vehicle stability prior to striking the next check dam.

Unfortunately, the consequences of a second vehicle impact with an adjacent check dam are unpredictable. Under this scenario, a vehicle would likely exhibit degraded stability combined with varying degrees of compressed and extended vehicle suspension after traversing a roadside slope, impacting the ditch bottom or check dam's approach slope, and then traversing or being launched over the first check dam. A combination of computer simulation modeling and full-scale vehicle crash testing would be required to determine safe horizontal distances between various rock check dams located in roadside ditches. In the absence of this detailed study, the research team attempted to prepare preliminary design and placement guidelines for roadside check dams using available information and engineering judgment.

The preliminary design guidelines, as presented in Table 13, were further evaluated to estimate a minimum horizontal spacing between rock check dams. A minimum spacing was deemed necessary due to an increased propensity for vehicular instabilities prior to and during a second impact with an adjacent check dam. Thus, an allowable recovery distance was considered necessary for an airborne vehicle to adequately stabilize after it re-contacts the ditch surface. A schematic of the vehicle (particle) trajectory, airborne distance, recovery distance, and minimum spacing is depicted in Figure 9. It should be noted that an allowable recovery distance would not be intended to guarantee sufficient time and distance to bring the vehicle back to its steady-state position. Rather, an allowable recovery distance would be expected to provide reasonable time and suitable distance to regain moderate suspension stability and allow for the vehicle's wheels to mostly remain in contact with the ground prior to traversing the next check dam. Therefore, the research team calculated the minimum spacing for check dams as the sum of (1) a vehicle's horizontal airborne distance and (2) an allowable recovery distance. Of course, the minimum spacing was based on several parameters such as vehicle approach speed, check dam height, and check dam approach slope.

Two methods were used to estimate an allowable recovery distance for adequately stabilizing an airborne vehicle after re-contacting the ditch surface, as depicted in Figure 9. The first method, Method 1, was based on providing an allowable recovery distance that is approximately equal to the vehicle's horizontal airborne distance after striking the first check dam. The second method, Method 2, utilized a time-based approach to determine an allowable recovery distance. For the later method, an allowable recovery distance was assumed equal to one second of travel time multiplied by the horizontal component of initial velocity. Results obtained using either method are summarized in Table 15.

For both methods noted above, the allowable recovery distance was based on the assumption that the horizontal component of the initial velocity would remain constant after re-contacting the ditch surface. However, it would seem reasonable that moderate speed reductions would likely occur as an errant, airborne vehicle re-contacts the ditch bottom and traverses up the second check dam structure. Thus, the allowable recovery distances determined above would likely provide a conservative estimate for the minimum spacing of check dams. This analysis was based on the assumption that the critical minimum spacing should only consider impact events with the first and second check dams.

The recommended guidance regarding the minimum spacing between sequentially-placed check dams based on head-on impact trajectories are provided in Table 15. As shown therein, the minimum spacing between 2-ft tall, rock check dams with 1V:6H approach slopes with 60 mph approach speeds was found to range between 176 and 178 ft. Further, the minimum spacing between 2-ft tall, rock check dams with 1V:4H approach slopes with 30 mph approach speeds was found to range between 70 and 78 ft.

Errant vehicles may strike the rock check dams with either head-on or oblique vehicle trajectories relative to the roadway. Thus far, the trajectory analysis and determination of minimum spacing only focused on a vehicle striking a check dam while traveling in a head-on orientation, as depicted in Path 1 of Figure 8. Alternatively, errant vehicles which encroach into a ditch may strike a check dam under oblique impact conditions, depicted by Path 2 of Figure 8. Under this scenario, an errant vehicle could strike a rock check dam, be launched into the air, and subsequently land on the back slope of the ditch instead of landing downstream in the relatively flat ditch bottom.

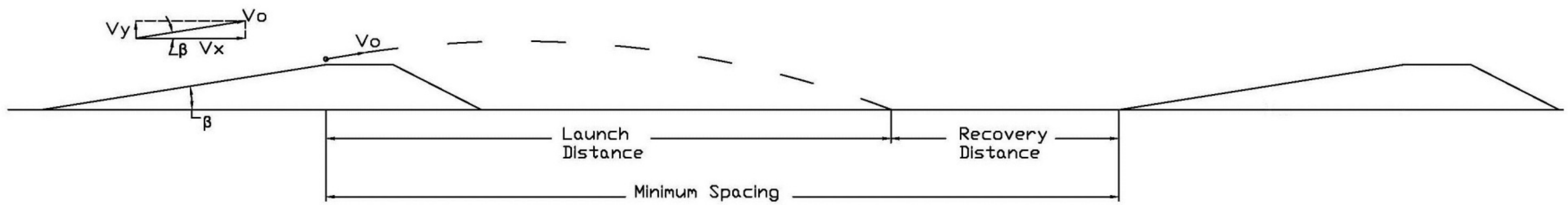

Figure 9. Particle Trajectory - Rock Check Dam Spacing Analysis

Table 15. Minimum Rock Check Dam Spacing – Head-on Impact

Design Conditions			Particle Trajectory		Allowable Recovery Distance		Minimum Spacing	
Approach Slope (V:H)	Resultant Approach Speed (mph)	Maximum Center Height (ft)	Maximum Height[1] (ft)	Launch Distance[2] (ft)	Method 1: Horizontal Airborne Distance[3] (ft)	Method 2: 1-sec Travel Distance (ft)	Method 1: Horizontal Airborne Distance[3] (ft)	Method 2: 1-sec Travel Distance (ft)
1:4	30	3	4.8	37	37	43	74	80
1:4	30	2	3.8	35	35	43	70	78
1:6	45	3	4.8	58	58	65	116	123
1:6	45	2	3.8	54	54	65	108	119
1:6	60	2	5.2	89	89	87	178	176
1:10	60	3	4.2	68	68	88	134	156
1:10	60	2	3.2	63	63	88	126	151

[1] – Calculation includes initial dam height
[2] – Based on flat ditch (i.e., no grade) assumption
[3] – Method 1 allowable recovery distance assumed equal to horizontal airborne distance
[4] – Method 2 allowable recovery distance assumed equal to 1 second times horizontal component of initial velocity

Unfortunately, no preliminary trajectory analysis was performed for oblique impact events for several reasons. First, the number of possible combinations of ditch configuration, check dam size, and encroachment conditions was deemed too large and complex for performing simple hand calculations. Second, a trajectory analysis involving vehicular impacts with a check dam and back slope was better suited for investigation using computer simulation modeling, as planned for the Phase II continuation study. For oblique impact scenarios, the determination of a vehicle's attitude and vehicle-to-ground contact location would be highly dependent on many factors, including: (1) vehicle encroachment conditions (angle and speed); (2) ditch geometry (i.e., depth, width, and side slope); (3) location of the check dam relative to the encroachment path; and (4) check dam geometry.

For the above mentioned reasons, the preliminary guidelines and minimum spacing presented herein were based on head-on impact events with a rock check dam installed on level terrain. Simplified assumptions relative to horizontal airborne and allowable recovery distances were made as well. Under the subsequent phases of the study, it is recommended that a combination of numerical computer simulations and full-scale vehicle crash testing be used to evaluate the safety and adequacy of the preliminary design and placement guidelines. Also, due to the complexities and uncertainties associated with tracking vehicle traversals of rock check dams, future research regarding non-tracking impact conditions should not yet be considered.

4.3 Rock Ditch Liners

Following a review of the State DOT standards, policies, and practices, it is evident that rock ditch liners should be sufficiently entrenched within the soil ditch so that the final upper rock surface is approximately flush with the non-lined, adjacent soil terrain. The entrenchment depth or liner thickness is assumed to be equal to at least two times the average width of the D_{50} rocks contained therein. In addition, a filter fabric should also be installed directly on the ground before any rock is placed to line the ditch surfaces. According to FHWA's HEC 15 [20], gravel is often used to create a transition from soil to riprap. Therefore, consideration should also be given to lining the shoulder with gravel whenever a rock ditch liner is placed adjacent to a roadway. Given these design considerations, it is recommended that the side slopes of a trapezoidal ditch be no steeper than 1V:3H when constructed with a generally-smooth, rock lining surface.

Additional design criterion for rock ditch liners pertain to the size of rock or riprap, which is highly dependent on shape and size of the ditch as well as the expected runoff flows. As a result, the selection of a standard size of riprap or rock may not be reasonable. Rather, it may be necessary to select a reasonable but critical rock size for use in the preliminary design guidelines and for later evaluation within a Phase II computer simulation and full-scale crash testing program. First, the size of rock or riprap should provide adequate resistance to movement over a broad range of flow velocities. Second, the gradation of rock or riprap must allow for errant vehicles to safely traverse a ditch lined with compacted rock or riprap within the soil surfaces.

As discussed previously, vehicular impacts with large rocks would likely pose an increased risk to motorists as compared to vehicular impacts with small rocks. There are safety concerns regarding excessive rock exposure above the general upper plane of a ditch liner. Vehicular impacts into a large, exposed rock could lead to an increased propensity for a vehicle to become airborne or for a vehicle's undercarriage to snag on a jagged rock. Second, large exposed rocks may also result in increased propensity for vehicular instabilities while traversing a rock-lined ditch. As such, it would seem reasonable and practical to select a rock or riprap gradation that allows for safe ditch traversals.

After considering the common rock sizes noted in Table 2 along with existing AASHTO guidelines for limiting the height of exposed elements above grade, the research team selected a D_{50} rock size ranging from 6 to 8 in. and a maximum rock size (i.e., D_{100}) ranging from 10 to 12 in. These rock or riprap sizes were deemed reasonable; since, they were well represented within the survey data obtained from selected State DOTs. It is the researcher's opinion that the use of these rock sizes should be capable for limiting excessive rock exposure to 4 to 6 in. Based on these selections, preliminary design and placement guidelines were prepared for rock ditch liners and are as follows:

1. When low-flow ditch velocities require a D_{50} rock or riprap size ranging from 6 to 8 in. and a maximum rock size (i.e., D_{100}) ranging from 10 to 12 in., the lining material can simply be placed, but preferably plated.

2. When ditch flow velocities reach a point when it is necessary to exceed the rock or riprap sizes noted above, wire-enclosed rock liners containing smaller rocks should be used.

3. When water flows are extremely high, grouted rock or riprap liners, like California's rock blanket shown in Figure 5, should be implemented.

4. As best as possible, the maximum rock exposure above the general upper plane of the ditch liner should be limited to 4 to 6 in.

These preliminary design and placement guidelines for rock ditch liners are shown in Figure 10. If desirable, flow velocities of rock-lined ditches can be determined using the equations found in FHWA's HEC 15.

It should be noted that the rock or riprap sizes presented herein were selected using a combination of engineering judgment, State DOT survey data, and the best available information. In addition, the relative smoothness of rock ditch liner will be totally dependent on the quality of construction and experience of the contractor. Finally, these preliminary guidelines were prepared with motorist safety in mind. However, the actual safety performance of these guidelines can only be assessed through the use of full-scale crash testing.

4.3.1 Safety Considerations

The Phase I preliminary design and placement guidelines for ditch liners were based on the assumption that a relatively-stable vehicle initially strikes a relatively-smooth ditch side slope or ditch bottom. However, it is known that tracking vehicles which leave the roadway and traverse over sloped roadside terrain can exhibit moderate roll and/or pitch angles prior to re-contacting a side slope or ditch bottom. These initial vehicle motions, combined with vehicle contact with excessively-exposed rock and/or a somewhat rough rock lining, could lead to significant concern for vehicular instability while traversing the drainage channel.

Historically, computer simulations and crash tests have demonstrated that high-speed passenger vehicles can safely traverse smoothly-graded, soil terrain 1V:3H fill slopes as well as trapezoid or flat bottom ditches with 1V:3H side slopes [23-24,27-29]. However, the researchers believed that rock-lined ditches would likely degrade vehicular stability for all reasonable sizes of rock or riprap. Thus, the prior acceptable configurations for soil-based, roadside fill slopes and ditches were flattened to account for increased vehicular instabilities as a function of design speed. The preliminary guidelines for rock ditch liners were conservatively configured with side slopes which varied as a function of design speed. At the present, side slopes of 1V:3H, 1V:4H, and 1V:6H were recommended for rock-lined ditches with design speeds of 30, 45, and 60 mph, respectively, as shown in Table 16.

Table 16. Preliminary Design Guidelines – Rock Ditch Liners

Speed (mph)	Maximum Ditch Side Slope (V:H)
30	1:3 of flatter
45	1:4 or flatter
60	1:6 or flatter

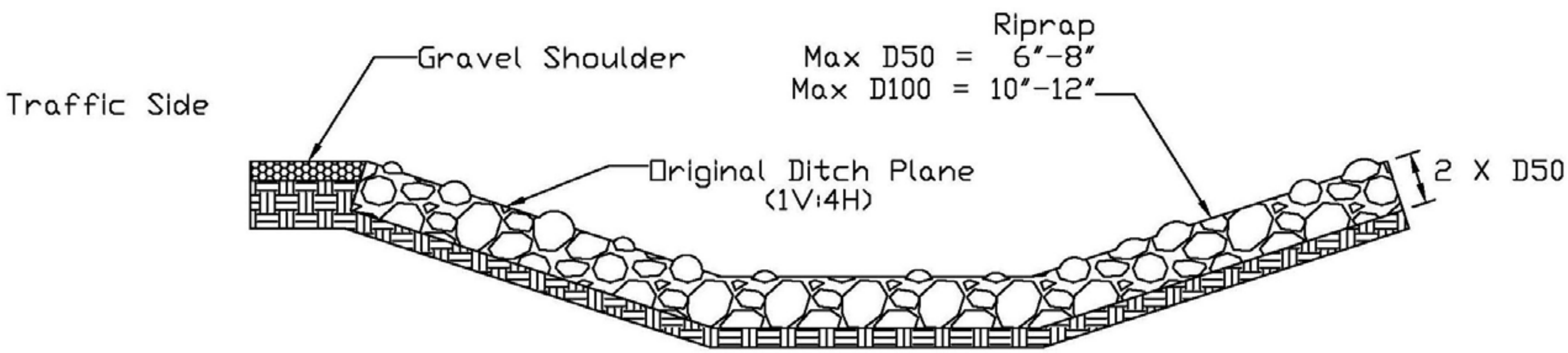

Figure 10. Preliminary Rock Ditch Liner Guideline

At this time, there exists uncertainty as to how an irregular rock liner will affect vehicle stability during initial impact and while traversing the ditch surface. Although it is highly desirable for a rock ditch liner to be relatively smooth, it is impractical to eliminate every rock protrusion above the general top plane of the ditch surfaces. Sharp edges of protruded rock or riprap could have severe consequences for an errant vehicle. For example, excessive protrusions could contact or snag on a vehicle's undercarriage or steering mechanisms, thus resulting in loss of vehicle control and/or increased instabilities. In addition, sharp rock protrusions could increase the propensity for tire blowouts as well as cause significant damage to the wheel and suspension assemblies. At this point, the effect that these behaviors have on vehicle performance and stability is not clear. Numerical computer simulation and experimental crash tests would be required to investigate and evaluate whether rock-lined surfaces greatly affect the ability for passenger vehicles to traverse slopes and ditches.

Thus, future research with numerical computer simulation and full-scale vehicle crash testing is recommended to evaluate the safety and adequacy of the preliminary design and placement guidelines for rock ditch liners as well as to make modifications to the guidelines, if deemed necessary. Also, due to the complexities and uncertainties associated with tracking vehicle traversals of rock ditch liners, future research regarding non-tracking impact conditions should not yet be considered.

5 FUTURE TESTING AND MODELING RESEARCH PLAN

5.1 Phase II – Computer Simulation Modeling

The second phase of this research study will be devoted to modeling vehicular impacts with rock ditch liners and rock check dams. In particular, a vehicle computer code which can accurately simulate the dynamics of vehicle tire and suspension assemblies will be chosen (e.g., LS-DYNA, HVOSM, etc.). A series of full-scale tests will be conducted to obtain useful information about the vehicle kinematics when traversing uneven surfaces. The collected data will be used to calibrate computer models which will then be used to identify critical impact scenarios for each device from those suggested in the preliminary guidelines presented in the previous chapter. A test matrix will be developed based on the simulation results. The following sections present a detailed description of the main tasks of Phase II for rock ditch liners and rock check dams, respectively.

5.1.1 Rock Ditch Liners

5.1.1.1 Task 1

The first task will involve assessing the stability of a vehicle when traversing a rock liner on level terrain, through the use of full-scale testing. Initially, the rock gradation suggested in the preliminary guidelines of Phase I will be considered. The rocks composing the liner will be dumped into place and the average protrusion height resulting from this practice will be observed. Both low- and high-speed traversals of the liner will be examined (i.e., 30, 45, 60 mph). At a relatively low speed, the tires of a vehicle traversing a non-uniform liner will be more likely to slip between the cracks of the liner, ultimately resulting in an increased propensity for the under carriage of the vehicle to snag on a rock. Conversely, the suspension system of a vehicle traversing a rugged liner at a relatively high speed is more likely to become unstable.

Due to its lower profile and smaller tire size, the 1100C vehicle is likely to be more prone to snag potential and overall instability than the heavier 2270P. Therefore, testing on level terrain will be initially conducted only with the 1100C vehicle in order to evaluate various rock gradations. If necessary, the liner gradation will be iteratively altered until a conservatively safe vehicle traversal is obtained. An examination of the 2270P pickup will only be conducted once a safe gradation has been selected for the 1100P vehicle.

5.1.1.2 Task 2

The results from Task 1 will be used to calibrate a numerical model to simulate impacts with rock ditch liners. In particular, the model has to be able to reproduce the dynamics of the vehicle suspensions, potential tire de-bedding and ejection or relative movements of rocks.

The guidelines presented in Table 16 will be modeled with the 1100C and 2270P vehicles, respectively, to determine critical impact scenarios and to form a matrix of full-scale tests for Phase III. Parameters to be considered in this matrix will include, but are not limited to the following: vehicle impact speed, vehicle encroachment angle and ditch side slope steepness.

5.1.2 Rock Check Dams

5.1.2.1 Task 1

The first task will involve assessing the stability and trajectory of a vehicle launched from a high-speed highway driveway. Although prior research studies have investigated this event, the types of vehicles utilized in those studies are no longer representative of the vehicle fleet circulating on the roadways today. Therefore, full-scale head on impacts with 1100C and 2270P vehicles will be conducted to examine vehicle launch distances and vehicle responses to such an event. In particular, the distance to which a vehicle regains a substantial amount of stability after landing will be observed.

5.1.2.2 Task 2

The results from Task 1 will be used to calibrate a numerical model to simulate impacts with rock check dams. Initially, the dam will be modeled as a solid ramp with a rough surface. This assumption will be verified from the full-scale tests in Phase III. The guidelines presented in Table 13 will be modeled with the 1100C and 2270P vehicles to determine critical impact scenarios and to form a matrix for testing in Phase III. Parameters to be considered in this matrix will include, but are not limited to the following: vehicle impact speed, vehicle encroachment angle, steepness of ditch side slope and dam approach slope, and dam height.

5.2 Phase III – Full-Scale Testing

The third phase of this research study will be devoted to investigating the critical impact scenarios for rock ditch liners and rock check dams determined using computer simulations from Phase II. Results from these tests will be used to create final safety guidance for each feature. Computer models will continuously be refined during the extent of this process. In the event that the computer simulation results predicted in Phase II are not consistent with the full-scale tests, the test matrix may be re-evaluated and altered accordingly.

5.2.1 Rock Ditch Liners

5.2.1.1 Task 1

Full-scale tests into a rock-lined, trapezoidal ditch will be conducted with the 1100C and 2270P vehicles according to the gradation and critical impact scenarios determined from Phase II.

5.2.1.2 Task 2

The results from Task 1 will be used to refine the computer model developed in Phase II for rock ditch liners.

5.2.1.3 Task 3

Finally, the following safety guidelines will be developed for this device: (i) maximum side slope for a given speed and (ii) maximum rock gradation.

5.2.2 Rock Check Dams

5.2.2.1 Task 1

Full-scale tests will be conducted into a trapezoidal ditch with the 1100C and 2270P vehicles according to the gradation and critical impact scenarios determined from Phase II.

5.2.2.2 Task 2

The results from Task 1 will be used to refine the computer model developed in Phase II for rock check dams.

5.2.2.3 Task 3

Finally, the following safety guidelines will be developed for this device: (i) maximum approach slope for a given speed (ii) maximum height for a given speed and (iii) minimum spacing between dams.

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7 APPENDICES

Appendix A. Selected State DOT Standards for Erosion Control Devices

Selected State DOT standard plans for erosion control devices are presented in the following section to illustrate various aspects of typical practice. Figures include rock check dams and rock ditch liners.

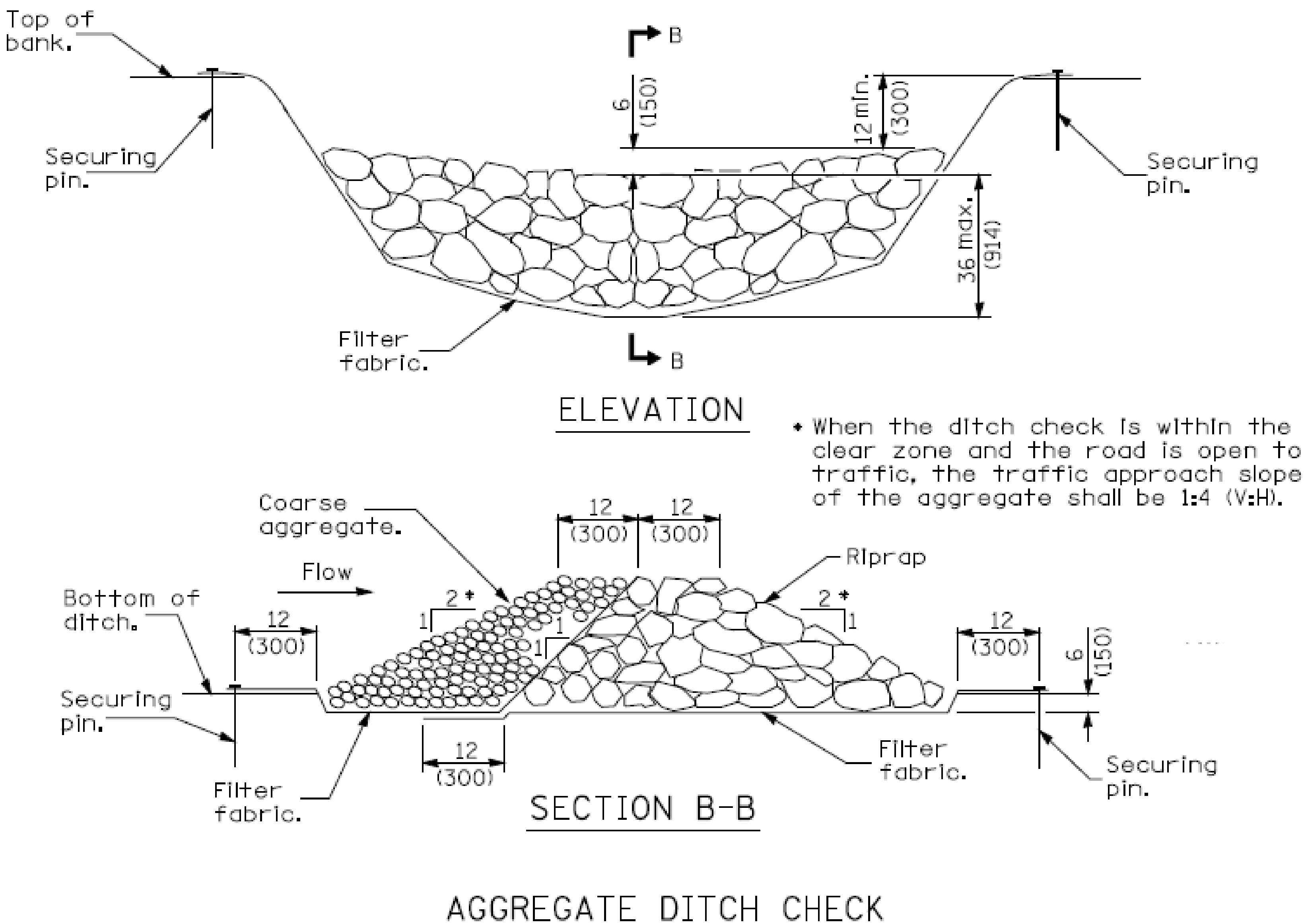


Figure A-1. Illinois DOT Rock Check Dam Specification [7]

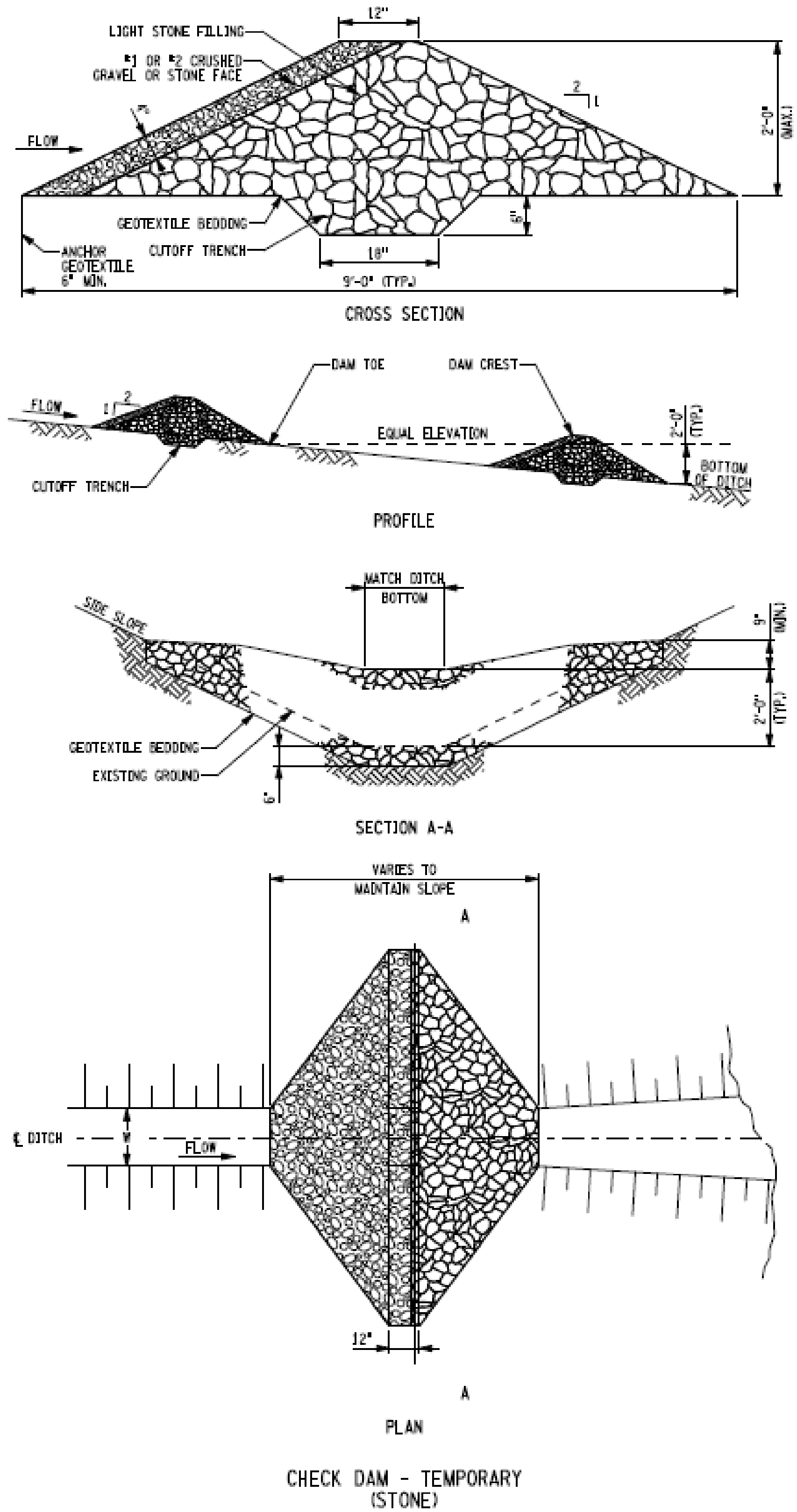


Figure A-2. New York DOT Rock Check Dam, Temporary [12]

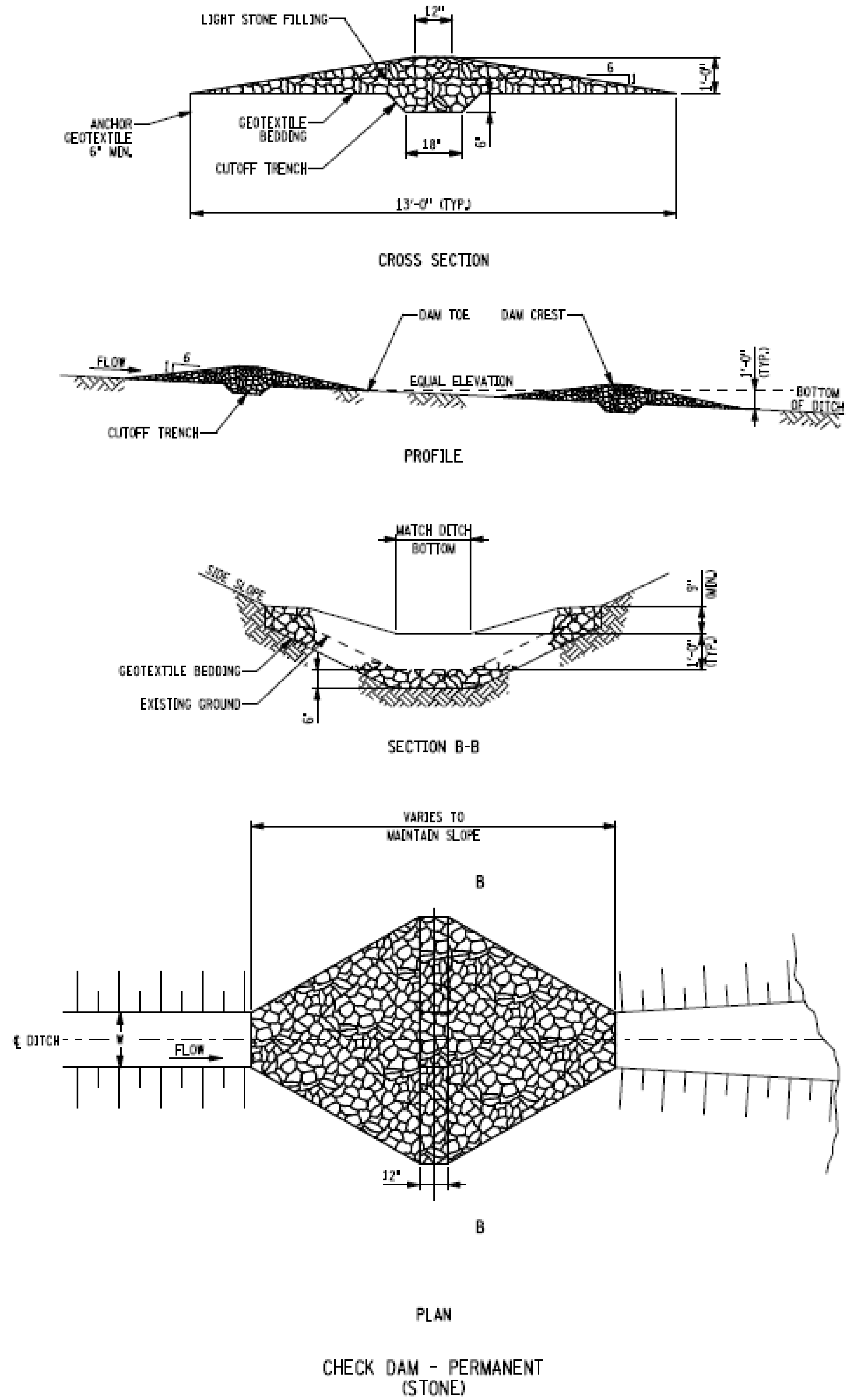


Figure A-3. New York DOT Rock Check Dam, Permanent [12]

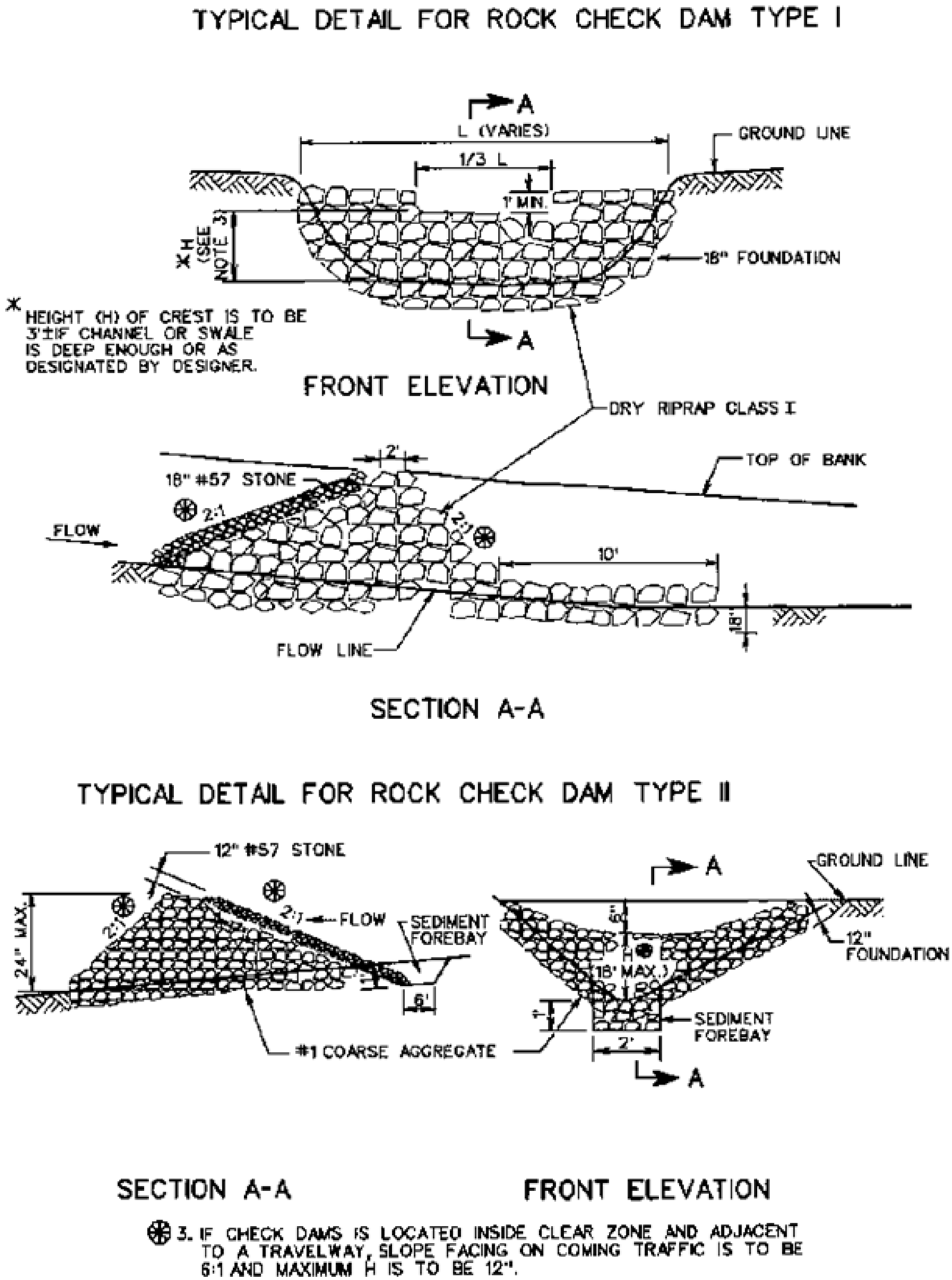
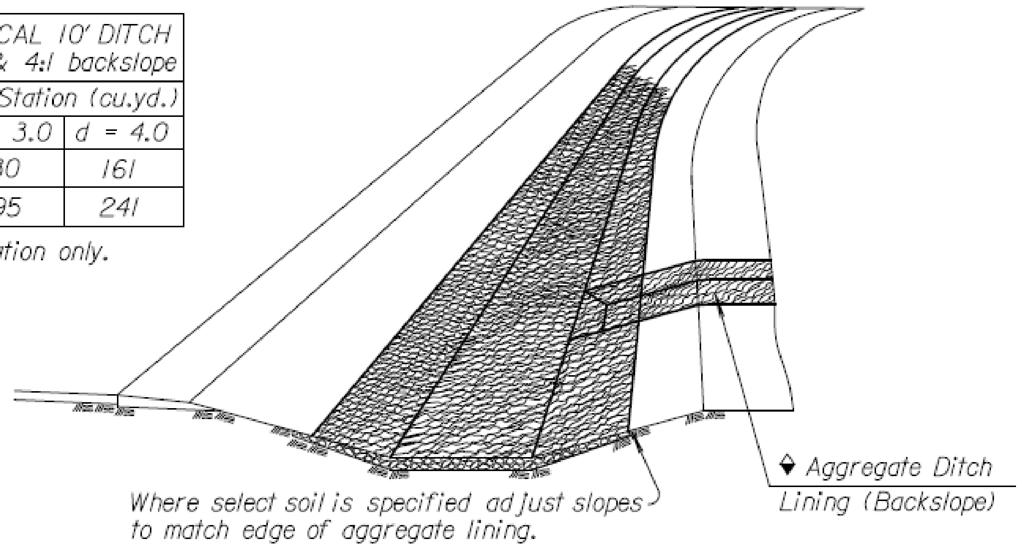


Figure A-4. Virginia DOT Rock Check Dam Specification [16]

			QUANTITIES FOR TYPICAL 10' DITCH with 6:1 shoulder slope & 4:1 backslope			
D_{50}	T	◭	Approx. Excavation per Station (cu.yd.)			
			d = 1.0	d = 2.0	d = 3.0	d = 4.0
4"	12"	8"	68	99	130	161
6"	18"	12"	102	148	195	241

Note: Quantities provided for information only.



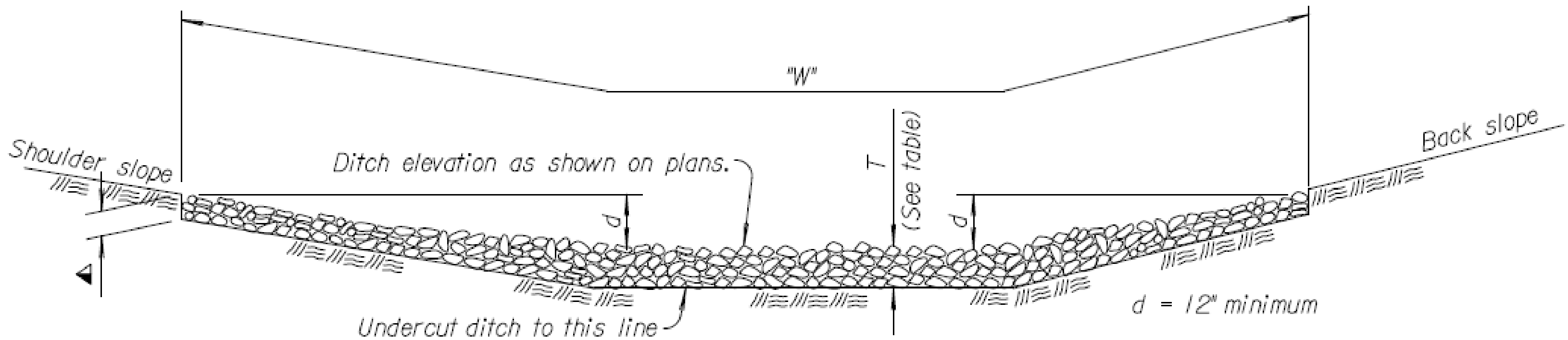


Figure A-5. Kansas DOT Rock Ditch Liner Specification [9]

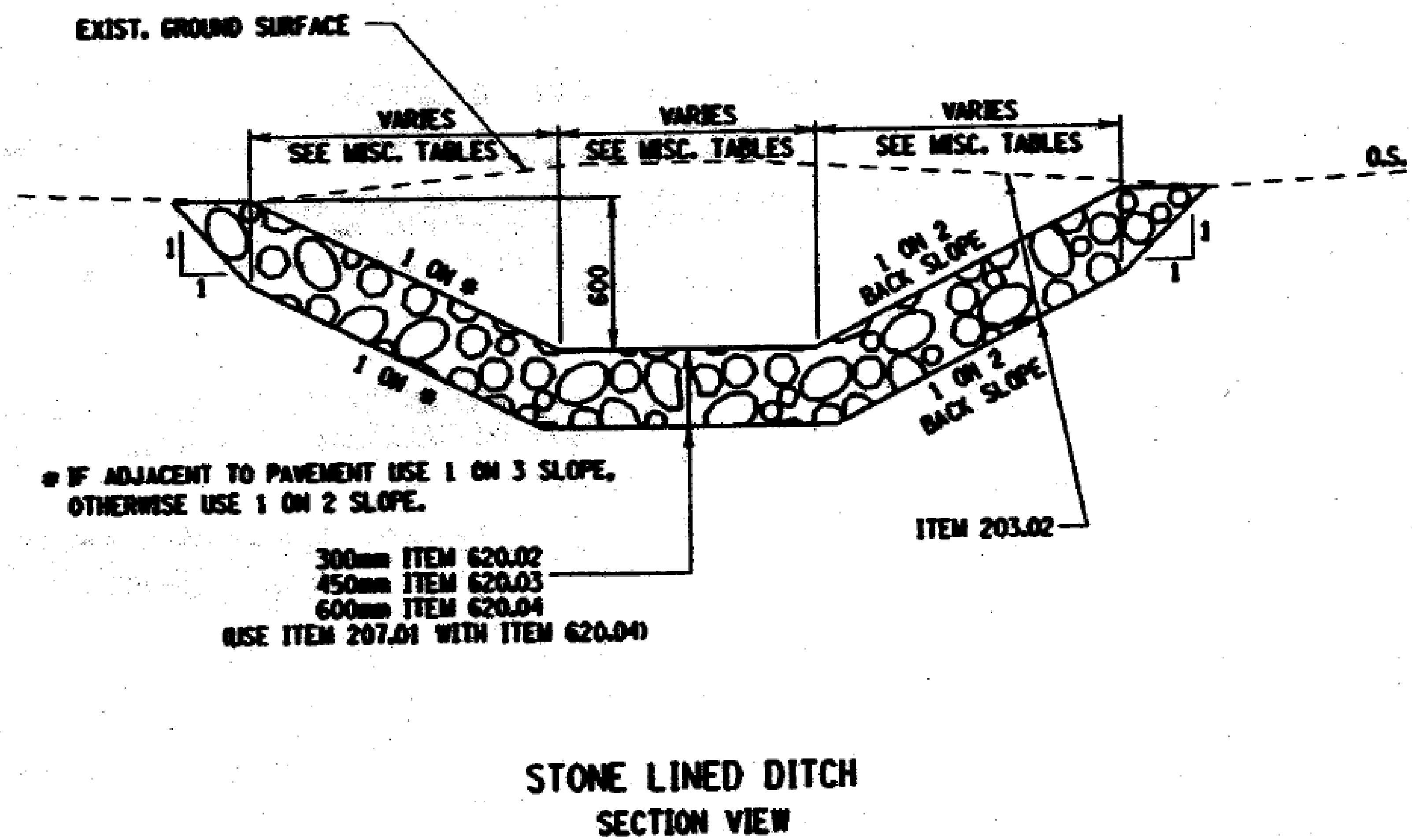


Figure A-6. New York DOT Rock Ditch Liner

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