ARIZONA DEPARTMENT OF WATER RESOURCES
FLOOD WARNING AND DAM SAFETY SECTION

State Standard

for

Watercourse System Sediment Balance

Under authority of ARS 48-3605(a), the Director of the Arizona Department of Water Resources establishes the following standard for identification of and development within erosion hazard areas and areas affected by a net system sediment deficit or surplus in Arizona:

The guidelines outlined in State Standard Attachment 5-96 entitled "Watercourse System Sediment Balance" or by an alternative procedure reviewed and accepted by the Director will be used in the identification of, or regulation of development within erosion hazard areas, and watercourses affected by a net system sediment deficit or surplus in Arizona for fulfilling the requirements of Flood Insurance Studies, and local community and county flood damage prevention ordinances.

For the purpose of application of these guidelines, erosion hazard area and watercourse system sediment balance standards will apply to all watercourses identified by the Federal Emergency Management Agency as part of the National Flood Insurance Program, all watercourses which have been identified by the local floodplain administrator as having significant potential flood hazards and all watercourses with drainage areas more than 1/4 square mile or a 100-year discharge estimate of more than 500 cubic feet per second. Application of these guidelines will not be necessary if the local community or county has in effect a drainage, grading or stormwater ordinance which, in the opinion of the Department, results in the same or greater level of flood protection as application of these guidelines would ensure.

This requirement is effective October 1, 1996. Copies of this State Standard and State Standard Attachment 5-96 can be obtained by contacting the Department's Flood Warning and Dam Safety Section at (602) 417-2445.

STATE STANDARD 5-96 **SEPTEMBER 1996**

NOTICE

This document is available in alternative formats. Contact the Department of Water Resources, Flood Warning and Dam Safety Section at (602) 417-2445 or (602) 417-2455 (TDD).

ARIZONA DEPARTMENT OF WATER RESOURCES
FLOOD WARNING AND DAM SAFETY SECTION

Watercourse System Sediment Balance

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STATE STANDARD ATTACHMENT **SEPTEMBER 1996**
SSA 5-96

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Introduction

The National Flood Insurance Program regulations 44 CFR 60.5 require local communities to review permits for development with regard to erosion hazards in "flood-related erosion-prone areas". Specifically 44 CFR 60.5.a.2 states "...Require review of each permit application to determine whether the proposed site alterations and improvements will be reasonably safe from flood-related erosion and will not cause flood-related erosion hazards or otherwise aggravate the existing flood-related erosion hazard....".

This document contains three guidelines for identification of, and development within erosion hazard areas, watercourses with a net sediment deficit, and watercourses with a net sediment surplus. The three guidelines in this document each contain their own table of contents relevant to its particular subject. These guidelines are:

Guideline 1: Lateral Migration Setback Allowance for Riverine Floodplains in Arizona

Guideline 2: Channel Degradation Estimation for Alluvial Channels in Arizona

Guideline 3: Evaluation of River Stability Impacts associated with Sand and Gravel Mining

Guideline 1 presents procedures for estimating the size of buffer (setback distance) that shall be provided along watercourses to allow for the lateral migration that may occur during future floods. Three methods of setback evaluation are discussed -- a first level procedure to be applied in normal conditions, a second level procedure for use in demonstrating the erosion resistance of existing channel materials, and a third level procedure which may be applied in unusual circumstances, or where more definite dimensioning of lateral migration potential is desired.

Guideline 2 presents procedures that may be used for estimation of channel degradation in unlined watercourses within Arizona. Three levels of procedures are provided, with data requirements, procedural complexity, and accuracy of results all increasing as the analysis level is incremented. The Level I approach provides an initial estimate of local channel degradation potential for generally stable, natural channel conditions. The resulting initial estimate may be reduced through use of the more rigorous Level II methodologies. Level III procedures are outlined for situations that warrant more detailed channel degradation determination.

Guideline 3 presents general guidelines that have been developed for determination of the adequacy of buffer areas between proposed mining operations and active river channels, and procedures that are available for analysis of the effects of instream activities.

A large part of Arizona has a "Basin and Range" topography which consists of mountain "blocks" of hard rock areas and adjoining basins that are filled with sediments which have been deposited by water (alluvium). The mountain areas do not have a problem with channel migration due to the stability of bed rock and large fragment rock found there. Basin areas, or the valley and low land areas containing alluvium are characterized by sediments that are erodible. The many variables associated with channel lateral migration, sediment balance, river

mechanics, and hydraulic engineering preclude the development of a comprehensive design manual in this short document: therefore, these guidelines are intended to be utilized with good engineering judgement and common sense.

Within this document the following acronyms will be used:

ADWR	Arizona Department of Water Resources
FEMA	Federal Emergency Management Agency
NFIP	National Flood Insurance Program

GUIDELINE 1

Lateral Migration Setback Allowance for Riverine Floodplains in Arizona

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Introduction

The floodplain boundaries associated with a given watercourse are not fixed features if the channel shifts and migrates over the course of time. Lateral migration of river channels is commonly observed in the arid southwest, where the flows are predominantly ephemeral and the bed and banks tend to be erodible. The migration relocates the channel banks and redefines the location of the river for the current and subsequent flow events.

This document presents procedures for estimating the size of buffer (setback distance) that shall be provided along watercourses to allow for the lateral migration that may occur during future floods. Three methods of setback evaluation are discussed -- a first level procedure to be applied in normal conditions, a second level procedure for use in demonstrating the erosion resistance of existing channel materials, and a third level procedure which may be applied in unusual circumstances, or where more definite dimensioning of lateral migration potential is desired.

Procedure

General

Three levels of analysis procedures are presented for determination of recommended setback distances for development in areas adjacent to watercourses. The Level I procedure provides a reasonable estimate of safe setback distance under normal conditions, with minimal channel geometry and hydrologic information required in its application. The higher level procedures, Level II and Level III, are more rigorous means of determining lateral migration potential, requiring knowledge of site specific hydraulic and channel material characteristics. The Level II procedure is provided as a straightforward means of demonstrating the stability of channel banks, in cases where a developer or floodplain manager seeks to apply a lesser setback than may be computed through application of the Level I equations. A flowchart outlining the procedure is provided on the following page. The Level III approaches referenced may be used for this purpose as well, or may be required by the local regulating agency for analysis of areas of particular concern, such as the following situations where the Level I allowances or Level II evaluations may not fully demonstrate the lateral migration potential:

(i) areas where massive shifting of the river channel has been observed in the past;
(ii) areas undergoing channel filling (aggradation) to a significant degree;
or, (iii) areas where local river mining, channelization, or other modifications could result in flow redirection unanticipated in the development of the Level I or Level II approaches.

Level I

This level of analysis requires the following information:

Drainage area. The area of the watershed contributing to the site of interest. Drainage areas should be estimated conservatively to account for all possible sources of runoff. USGS topographic quadrangle maps usually provide sufficient detail for delineating watershed areas.

Peak discharge associated with the 100-year flood (Q_{100}). May be estimated using simplified methodologies such as ADWR State Standard #2 (SS 2-96), USGS regression equations, or other similar approximate method.

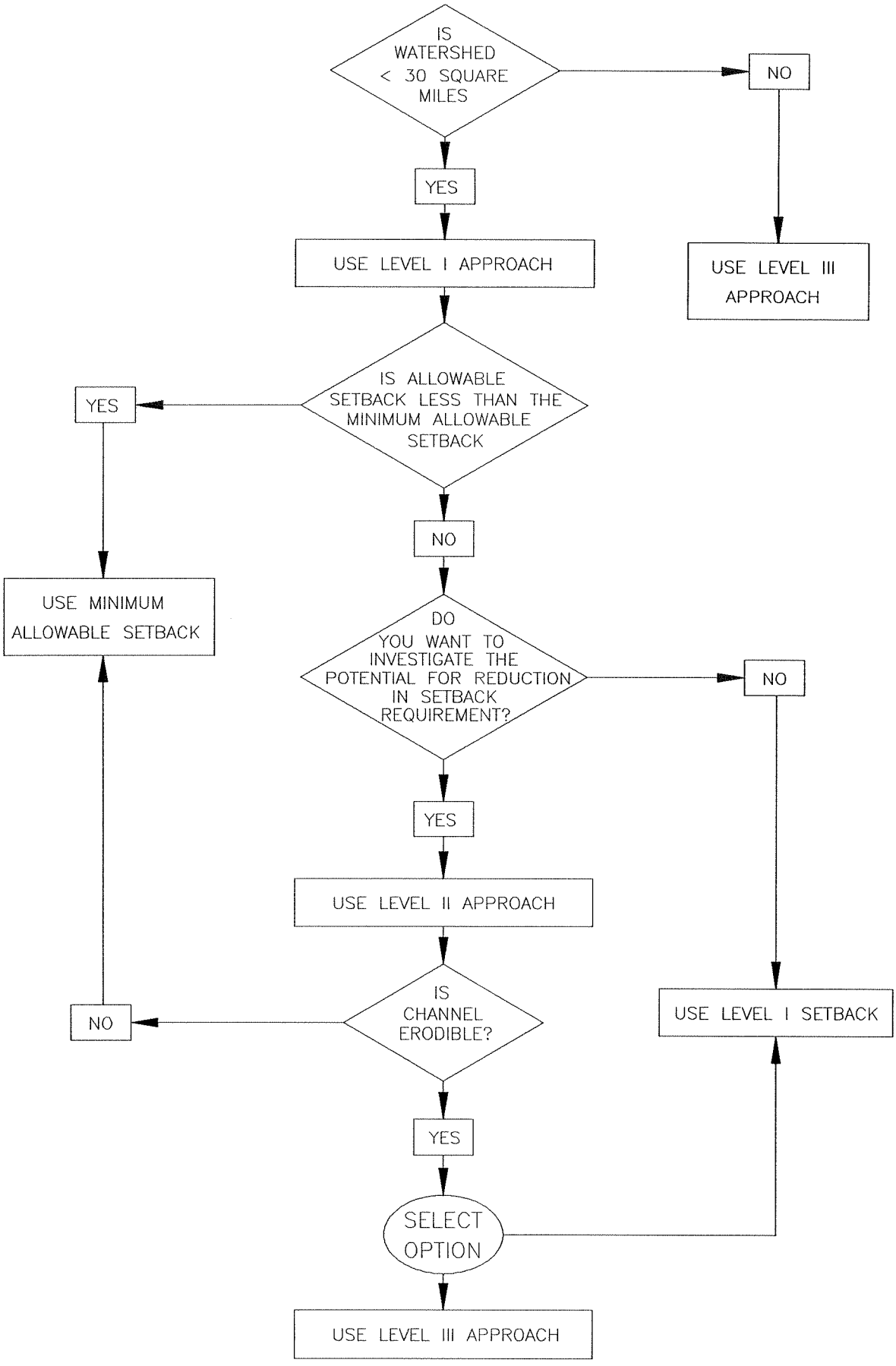
A Level I or Level II analysis should not be used on watercourses which have drainage areas greater than 30 square miles. If the watercourse has a drainage area greater than 30 square miles, a Level III analysis shall be performed.

For watercourses which have drainage areas of less than 30 square miles, the recommended setback allowances are as follows:

for straight channel reaches or reaches with minor curvature: $\text{setback} = 1.0(Q_{100})^{0.5}$

for channels with obvious curvature or channel bend: $\text{setback} = 2.5(Q_{100})^{0.5}$

where setback is in feet and Q_{100} is in cubic feet per second.

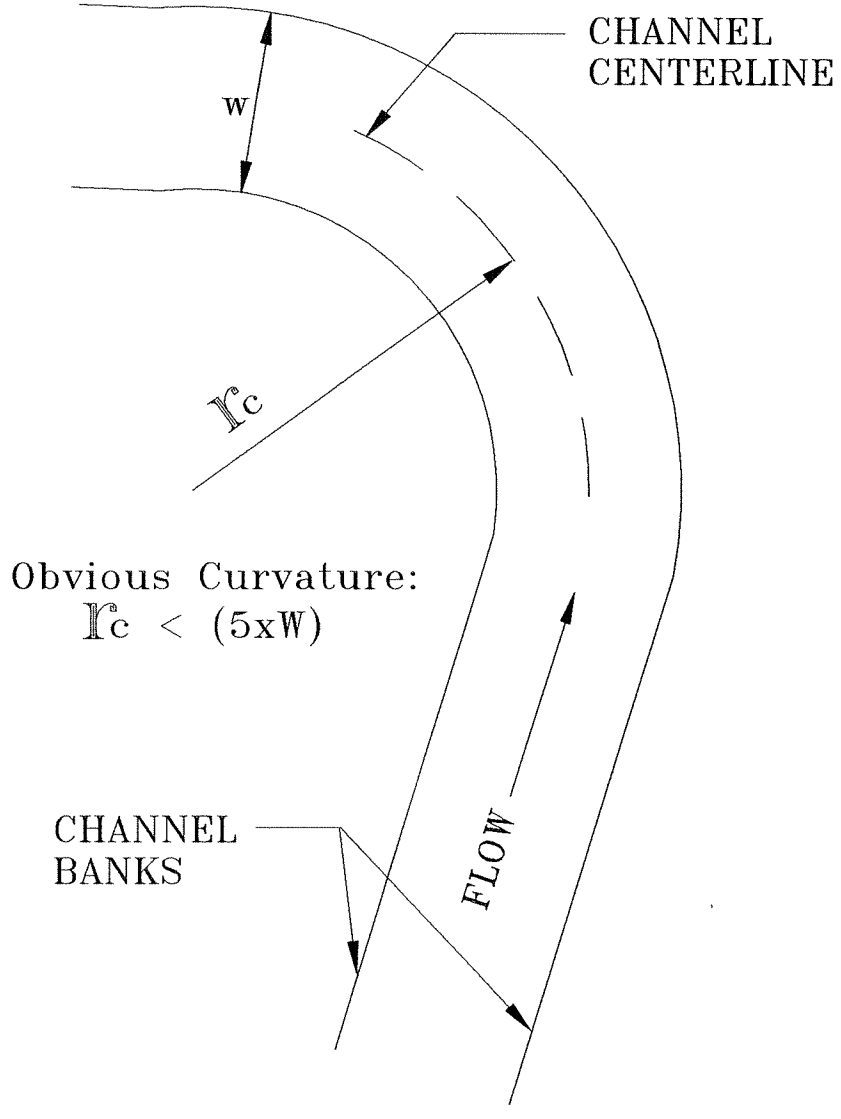

IS WATERSHED < 30 SQUARE MILES
NO
YES
USE LEVEL I APPROACH
USE LEVEL III APPROACH
IS ALLOWABLE SETBACK LESS THAN THE MINIMUM ALLOWABLE SETBACK
YES
NO
USE MINIMUM ALLOWABLE SETBACK
DO YOU WANT TO INVESTIGATE THE POTENTIAL FOR REDUCTION IN SETBACK REQUIREMENT?
NO
YES
USE LEVEL II APPROACH
IS CHANNEL ERODIBLE?
NO
USE LEVEL I SETBACK
YES
SELECT OPTION
USE LEVEL III APPROACH

FLOWCHART

In all cases for the Level I analysis, the minimum setback shall be 20 feet for straight channel reaches and 50 feet for channels with obvious curvature. Obvious curvature is defined as a channel centerline with a radius of curvature less than 5 times the channel top width.

The setback allowance is to be measured outward from the 100-year floodway or the top of the channel bank, whichever is greater. The above equations provide a larger setback allowance in areas with relatively tight channel bends. This larger setback allowance is to applied in areas adjacent to the outside bend of the channel.

A sketch is provided below to help differentiate between minor curvature and obvious curvature.



CHANNEL CURVATURE

Level II

This approach may be applied to demonstrate the stability of the channel material under 100-year flood conditions, and to justify a lesser setback requirement than that computed using the Level I equations. Setback allowances for conditions which pass one or more of the following channel stability approaches, and which are not located in areas of specific concern (i.e. areas adjacent to river mining sites, highly aggradational areas, or areas with artificial flow redirection) should be based on normal building safety criteria rather than the Level I equations presented above, since the bank limits would not be expected to change during the course of a 100-year design event.

Allowable velocity analysis

Under this approach, the velocity of the 100-year peak flow within the watercourse adjacent to the site under consideration is compared to an "allowable" velocity -- the velocity at and below which erosion is not expected to occur.

The basic maximum allowable velocity for unprotected earthen channels is determined from a relationship developed by the USDA Soil Conservation Service, shown in the attached **Figure 1**. In order to use this figure, flow must be classified as either sediment free or sediment laden. Sediment free flow is defined as flow in which fine material in suspension is at concentrations so low that it has negligible effect upon channel stability. Sediment free flows generally have sediment concentrations of less than 1,000 parts per million (ppm) by weight. Sediment-laden flows are classified as flows carrying sediments in concentrations equal to or exceeding 20,000 ppm, by weight.

Typical natural channel flows within Arizona can be characterized as sediment-laden when flow occurs. The sediment-free curve in Figure 1 should be used only under unusual circumstances, such as for runoff which emanates from a totally impervious watershed.

Use of Figure 1 requires that the D_{75} particle size (the size for which 75% of the sediment, by weight, is finer) be known for the soil forming the channel banks. This information can be obtained from a sieve analysis or alternate means should there be large fragmented rock present.

The basic allowable maximum velocity obtained from Figure 1 must normally be modified to account for variations in channel design. This is done by the use of correction factors for channel alignment, bank slope, and depth of flow. The equation for allowable velocity, V_a, in an unprotected earthen channel then becomes:

$$V_a = V_b \times C_a \times C_b \times C_d$$

where

V_a = Maximum allowable flow velocity, in feet per second;

V_b = Basic maximum allowable flow velocity obtained from Figure 1, in feet per second; and,

C_a , C_b , C_d = Correction factors for channel alignment, bank slope, and flow depth, respectively (see Figure 2 through 4).

Tractive stress analysis

Flowing water exerts a tangential boundary pull on the wetted perimeter of the channel boundary. The total force exerted on the boundary by the flow of water is called the tractive force. The tractive stress is the tractive force per unit area of the boundary. Tractive force and tractive stress are equal to the friction forces resisting the flow of water. Tractive stress can therefore be used as a method of determining the erodibility of an earthen channel. To accomplish this, the tractive stress is compared to an allowable tractive stress for the bed material.

Case 1: 0.25 inches $< D_{75} <$ 5.0 inches

The tractive stress acting on the soil grains in an infinitely wide channel can be computed from:

$$\tau_\infty = \gamma_w Y \left[D_{75}^{1/6} / 39n \right]^2 S_e$$

where

τ_∞ = Tractive stress for an infinitely wide channel, in lbs/ft^2;

γ_w = Unit weight of water = 62.4 lbs/ft^3;

D_{75} = Diameter of soil particle for which 75 percent of the total soil consists of smaller particles, in inches;

n = Manning's roughness coefficient for the channel;

Se = Energy slope of flowing water, in feet per foot; and,

Y = Depth of flow, in feet.

Once the tractive force for an infinitely wide channel is determined, it must be modified for a narrower trapezoidal channel. **Figures 5 through 7** give correction factors for tractive stresses in trapezoidal and curved channels. The correction factors

taken from these figures are multiplied by the tractive stress computed from the above equation to obtain the actual tractive stress.

The definitions of the symbols shown in Figures 5 through 7 are as follows:

τ_s	=	Actual maximum tractive stress on sides of straight trapezoidal channels, in pounds per square foot;
τ_{sc}	=	Actual maximum tractive stress on sides of trapezoidal channels within a curved reach, in pounds per square foot;
τ_{st}	=	Actual maximum tractive stress on sides of trapezoidal channels in straight reaches immediately downstream from curved reaches, in pounds per square foot;
Z	=	Channel side slope (horizontal/vertical), in feet per foot;
b	=	Channel bottom width, in feet;
y	=	Flow depth, in feet;
r_c	=	Radius of curvature of channel centerline, in feet; and,
L_c	=	Length of curve, in feet.

The actual tractive stress is compared to an allowable tractive stress to determine the propensity of the soil to erode under the expected hydraulic conditions. The allowable tractive stress is calculated by:

$$\tau_{ls} = 0.4 \left[(Z^2 - \text{Cot}^2 \phi R) / (1+Z^2) \right]^{1/2} D_{75}$$

where

τ_{ls}	=	Allowable tractive stress, in lb/ft^2; and,
ϕR	=	Angle of repose of soil, in degrees (see **Figure 8**).

Case 2: $D_{75} \leq 0.25$ inches

Under these conditions, a reference tractive stress as determined from **Figures 9 and 10** is used, following the steps listed below:

1. Determine the velocity (V), kinematic viscosity (v), and the energy slope (S_e) for the channel.

2. Enter Figure 9 or 10, from the top, with a value computed from the expression:

$$V^3 / (gvS_e)$$

Find the point of intersection of the above value and the value of:

$$V / (gk_sS_e)^{1/2}$$

where

k_s = Equivalent roughness height = D_{65}, in feet (the size for which 65% of the sediment, by weight, is finer).

3. Move horizontally along the figure to read the numerical value for:

$$V / (\tau/\rho)^{1/2}$$

where

τ = Reference tractive stress, in pounds per square foot;
V = Flow velocity, in feet per second; and,
ρ = Density of water = 1.94 slugs per cubic foot.

The value for τ can be found by equating the numeric value read from Figure 9 or 10 to this expression.

The maximum tractive stress on the sides of the channel, τ_s, can be computed from the reference tractive stress and a correction factor obtained from **Figure 11**. Figures 6 and 7 may be used to further modify the reference tractive stress for curved channel reaches. The adjusted reference tractive stress is then compared to the allowable tractive stress determined from **Figure 12**.

Curve number 1 in Figure 12 is to be used when the flow is expected to have a high sediment content. A high sediment content is considered to be 20,000 ppm, by weight, or more of sediment. Curve number 2 is to be used for watercourses with low sediment contents of no more than 2,000 ppm, by weight. This curve should only be used in association with areas of high impervious cover (> 50%) and/or downstream of urban area detention basins. Interpolate between curves 1 and 2 for water courses with known sediment content between 2,000 ppm and 20,000 ppm. Curve number 3 is to be used for watercourses conveying clear water, and should not be used unless unusual circumstances exist (e.g., runoff which emanates from a totally impervious watershed).

Tractive power analysis

Tractive power is defined as the product of the mean velocity of flow and the tractive stress. The tractive power analysis takes into consideration the effects of cementation,

partial lithification, and other long-term processes that can affect the ability of the channel to withstand erosion. Neither the velocity analysis nor the tractive stress analysis account for the effects of these long-term processes. With the tractive power approach, the stability of saturated soils comprising the channel banks is first assessed by the use of an unconfined compression test. The unconfined compressive strength (UCS) of these saturated embankment soils is then reduced by at least a factor of two, for design purposes, and compared to the tractive power of the flow by use of **Figure 13**. Conditions falling above the S-line in this figure are considered to be erosive, and those falling below the S-line are considered to be non-erosive. The method has some limitations due to variability and stratification of material along natural channels, and the limited data available to develop Figure 13.

Bank Lining Adequacy Analysis

Bank lining of some form may be proposed or already in place which may act to limit the lateral migration potential of the watercourse of concern. In some areas within Arizona, procedures are in place for assessment of the adequacy of the bank protection measures. For areas without standardized procedures, two references are recommended which detail evaluation procedures:

Design Manual for Engineering Analysis of Fluvial Systems, Arizona Department of Water Resources, 1985.

Standards Manual for Drainage Design and Floodplain Management in Tucson, Arizona, City of Tucson Department of Transportation, Engineering Division, 1989.

Level III

This level of analysis involves modeling the hydraulic and sediment transport characteristics of the local watercourse in order to simulate the erosion/sedimentation and channel deformation processes which are expected to occur in the area of concern. For this level of analysis, Level III hydrology shall be performed to generate required hydrographs. Level III analyses should be performed by persons with knowledge and experience in the fields of sediment transport and river geomorphology. It is recommended that any movable boundary river modeling used for establishment of setback be the culmination of a thorough analysis consisting of:

(1) evaluation of historical trends;
(2) qualitative analysis based on field evaluation and application of geomorphic principles;
and, (3) steady state hydraulic and sediment transport analysis.

Works Cited

Arizona Department of Water Resources, Flood Warning and Dam Safety Section, "Requirement for Floodplain Delineation in Riverine Environments - State Standard 2-96", July 1996.

Arizona Department of Water Resources, "Design Manual for Engineering Analysis of Fluvial Systems", March 1985.

City of Tucson Department of Transportation, Engineering Division. "Standards Manual for Drainage Design and Floodplain Management in Tucson, Arizona. December 1989.

Thomas, B.E., H.W. Hjalmarson, and S.D. Waltemeyer. "Methods for Estimating Magnitude and Frequency of Floods in the Southwestern United States." USGS Open-File Report. 1994. 93-419

Example Application

Example 1: Development Adjacent to a Watercourse

- **Problem Statement.** Single lot development proposed on 1-acre parcel bordered on one side by a small, earthen channel. The contributing watershed upstream of the site is 700 acres in area.

- **Objective.** Determine setback allowance from top of channel bank.

Level I Analysis

A 100-year peak discharge value of 530 cfs was determined from local hydrology methodology. The width of the 100-year floodplain in the site vicinity is 35 feet. The site is adjacent to the outside of a mild bend (i.e., radius of curvature greater than 5 times topwidth) in the channel.

Calculations:

A = 700 acres x (1 sq. mile/640 acres) = 1.09 sq. miles < 30 square miles

setback = $1.0\ (530)^{0.5}$ = 23 feet

Since the calculated setback is greater than the minimum recommended setback of 20 feet, use a 23 foot setback. The setback is measured from the top of the channel bank or the 100-year floodway limit, whichever is greater.

Level II Analysis

The developer would like to minimize the setback as much as possible without having to provide bank lining. Accordingly, the site specific hydraulic and grain size information is collected to check if erosion of the channel would be naturally limited. Local geometry for the channel is obtained using site measurements:

Bottom Width = 15 feet
Side Slope = 2 horizontal to 1 vertical
Channel Slope = Energy Slope = 0.01 feet/foot
Radius of curvature = 500 feet

The Manning n value for the channel is estimated at 0.030.

Using normal depth procedures, the hydraulic characteristics of the local channel under 100-year flood conditions are determined:

Flow Depth = 3.0 feet
Flow Velocity = 8.4 feet/second

Results of a sieve analysis of a local channel material sample yields the following information:

D_{75} = 4 mm = 0.013 ft = 0.16 inches
D_{65} = 1.2 mm = 0.0039 ft = 0.05 inches
D_{50} = 0.6 mm = 0.002 ft = 0.024 inches

Calculations:

(1) Allowable velocity approach, assuming sediment laden flow

Entering Figure 1 with D_{75} = 4 mm yields a basic velocity of 4.0 ft/sec.
Entering Figure 2 with r/w = 18.5 yields C_a = 1.0
Entering Figure 3 with Z = 2 yields C_b = 0.72
Entering Figure 4 with Depth = 3.0 feet yields C_c = 1.0

Maximum allowable velocity = (4.0)(1.0)(0.72)(1.0) = 2.9 ft/sec

Since the computed velocity of 8.4 ft/sec exceeds the maximum allowable velocity, erosion may be expected to occur.

(2) Tractive stress approach

Since D_{75} is less than 0.25 inches, the reference tractive stress method is used;

Assuming a water temperature of 60° F, the kinematic viscosity (ν) = 0.0000121 ft^2/sec, and the density (ρ) = 1.94 $slugs/ft^3$

Compute $V^3/(g\nu S_e) = 1.52 \times 10^8$

Compute $V/[(gD_{65}S_e)^{1/2}] = 237$

From Figure 9, $V/(\tau/\rho)^{1/2} = 19.0$

Solving the above equation yields $\tau = 0.38$ lb/ft^2.

From Figure 11, with bottom width over flow depth (b/Y) = 15/3 = 5, $\tau_s = (1.03)\tau = 0.39$ lb/ft^2.

From Figure 6, with radius of curvature over bottom width (r/b) = 500/15 = 33, $\tau_{sc} = 1.0\ \tau_s = 0.39$ lb/ft^2.
[Note that radius of curvature over bottom width is used in this procedure while radius of curvature over top width of flow is used in the allowable velocity approach.]

From Figure 12, Curve 1 (for high sediment content), the allowable tractive force is 0.083 lb/ft^2. Since 0.083 is less than 0.39, the channel is erosive.

(3) Tractive power approach

An unconfined compressive strength (UCS) test of the saturated embankment soils is performed, yielding a strength of 1000 lb/ft3.

Assuming half of this strength for design purposes, UCS_{design} = 500 lb/ft^3.

Compute tractive power = $V\tau_{sc} = 3.3$

From Figure 13, the condition falls above the S-Line, indicating that the channel is erosive.

All three approaches indicate that the channel is erosive. Therefore, the 23 foot setback allowance determined by Level I procedures can not be reduced unless the channel banks are armored or the channel is obviously in bedrock.

Level III Analysis

The conclusions derived from the Level II analysis and the small size of the development indicate that the Level III analysis would probably not be applied in this case. However, should the developer wish to proceed with the setback allowance investigation, a registered engineer with experience in sediment transport modeling could be employed for this purpose. The engineer would be expected to collect available historic information, document the historic planform changes to the watercourse under events of varying frequency, apply steady state hydraulic and sediment transport calculation procedures to determine the erosion/sedimentation characteristics of the local reach of

channel, and, potentially apply a moveable boundary river simulation model to quantify the changes likely along the study reach under design event conditions.

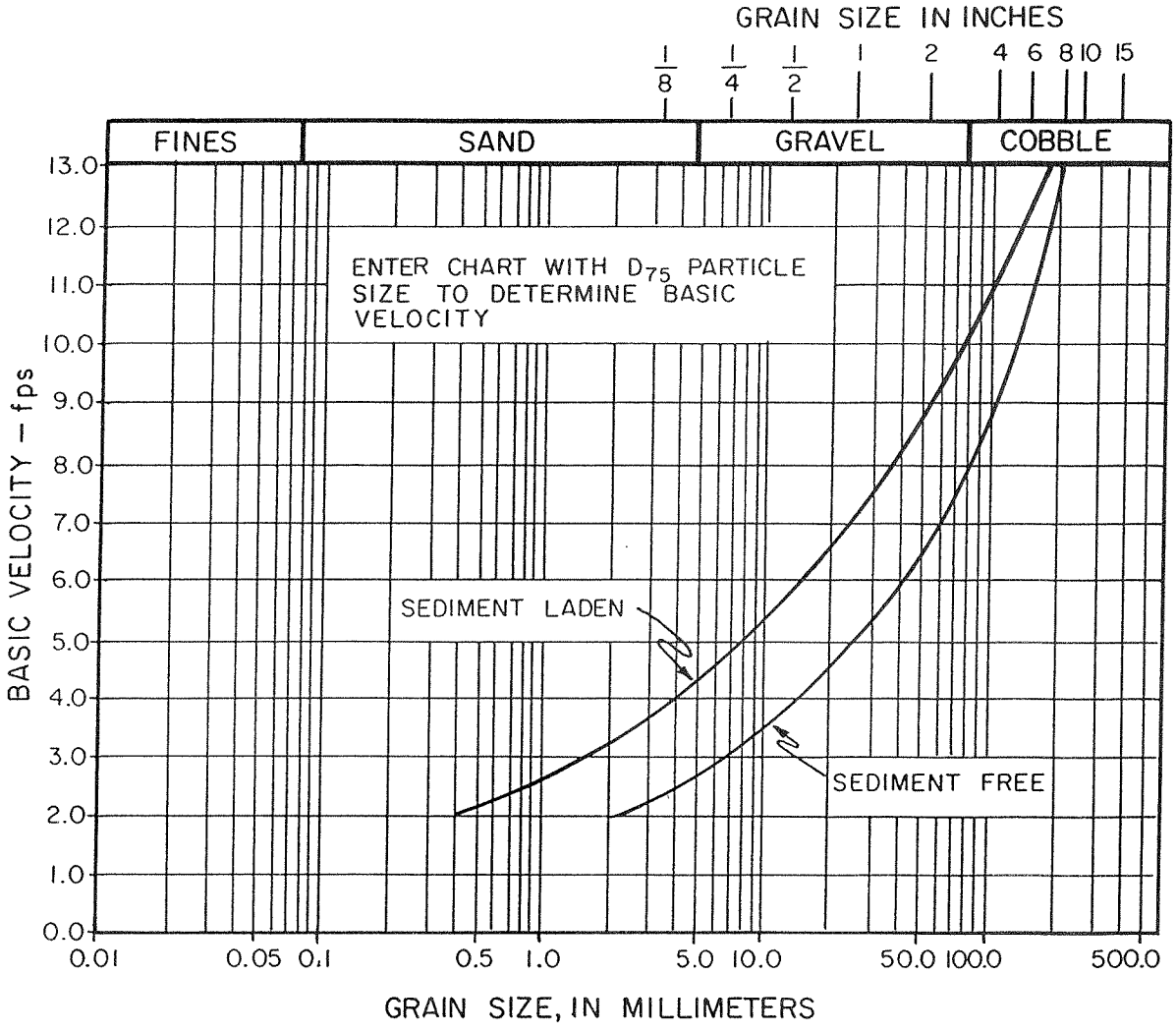


FIGURE 1

BASIC ALLOWABLE VELOCITY FOR EARTHEN CHANNELS

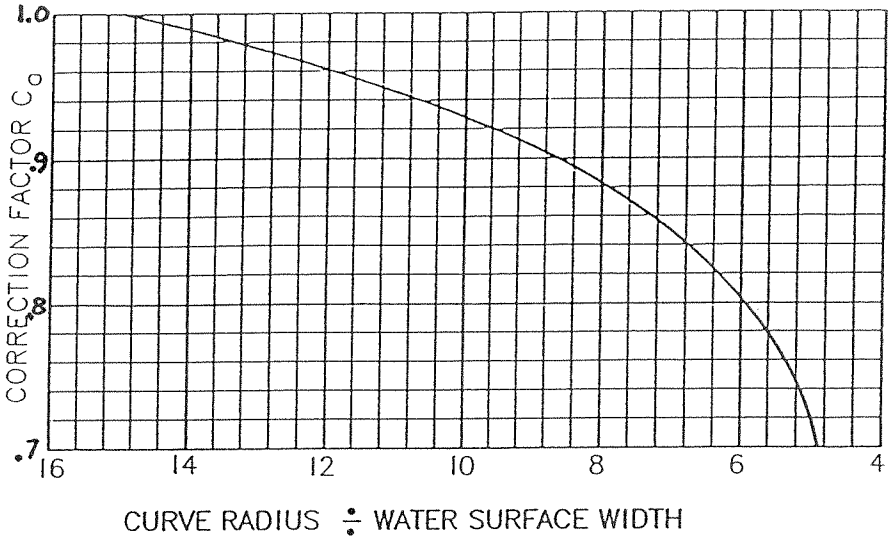


FIGURE 2

CORRECTION FACTOR C_a FOR CHANNEL ALIGNMENT

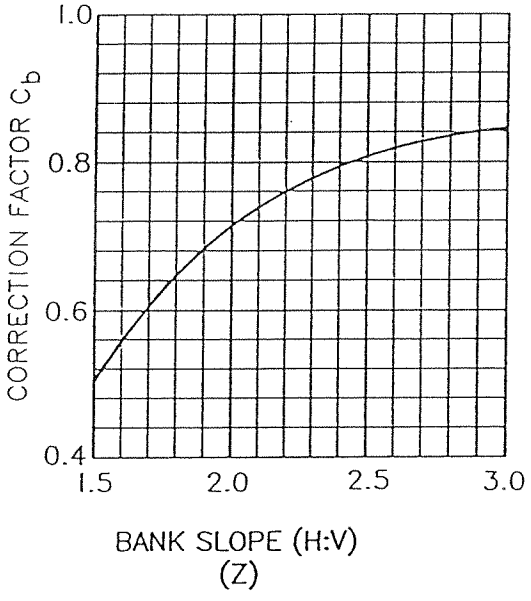


FIGURE 3

CORRECTION FACTOR C_b FOR BANK SLOPE

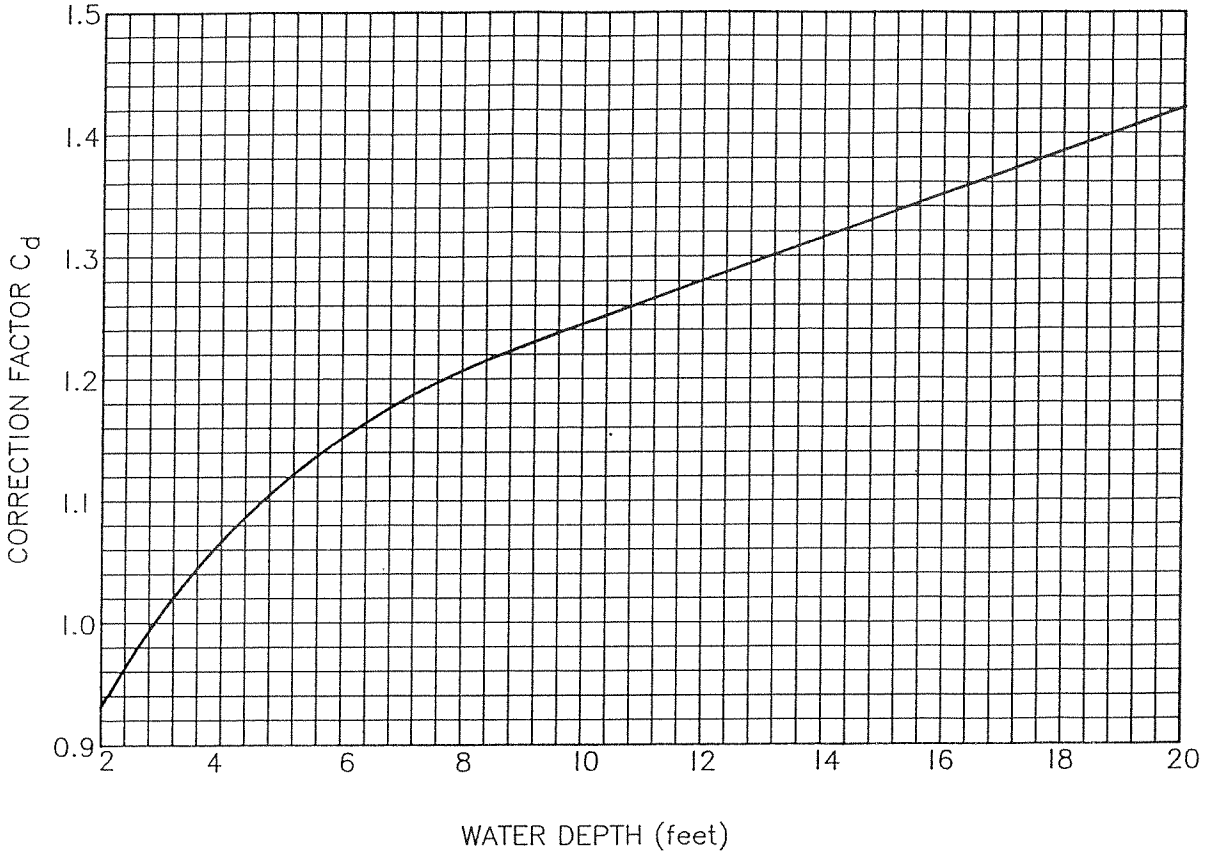


FIGURE 4

CORRECTION FACTOR C_d FOR DEPTH OF FLOW

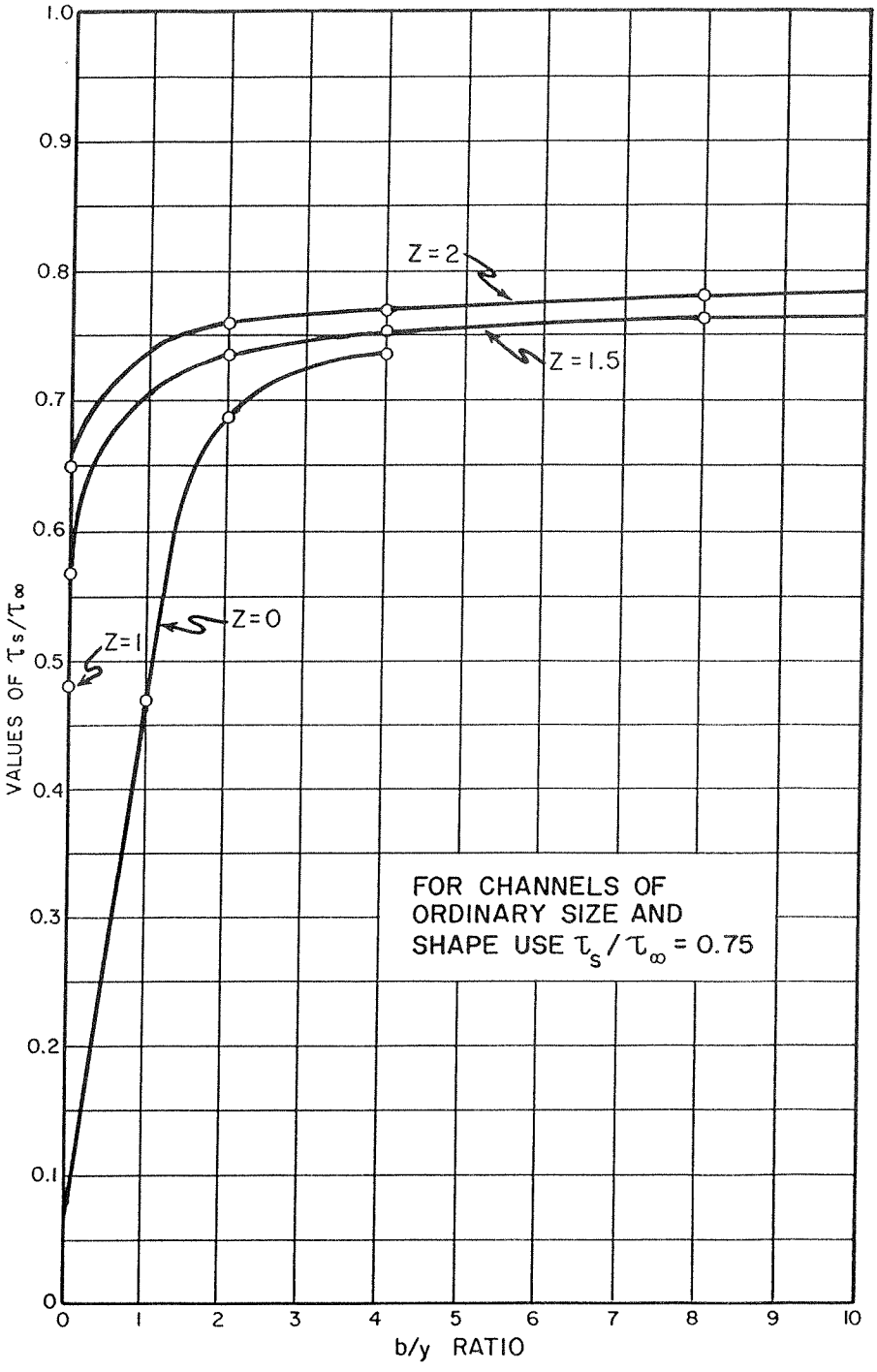


FIGURE 5

ACTUAL MAXIMUM TRACTIVE STRESS, Ts, ON SIDES OF STRAIGHT TRAPEZOIDAL CHANNELS

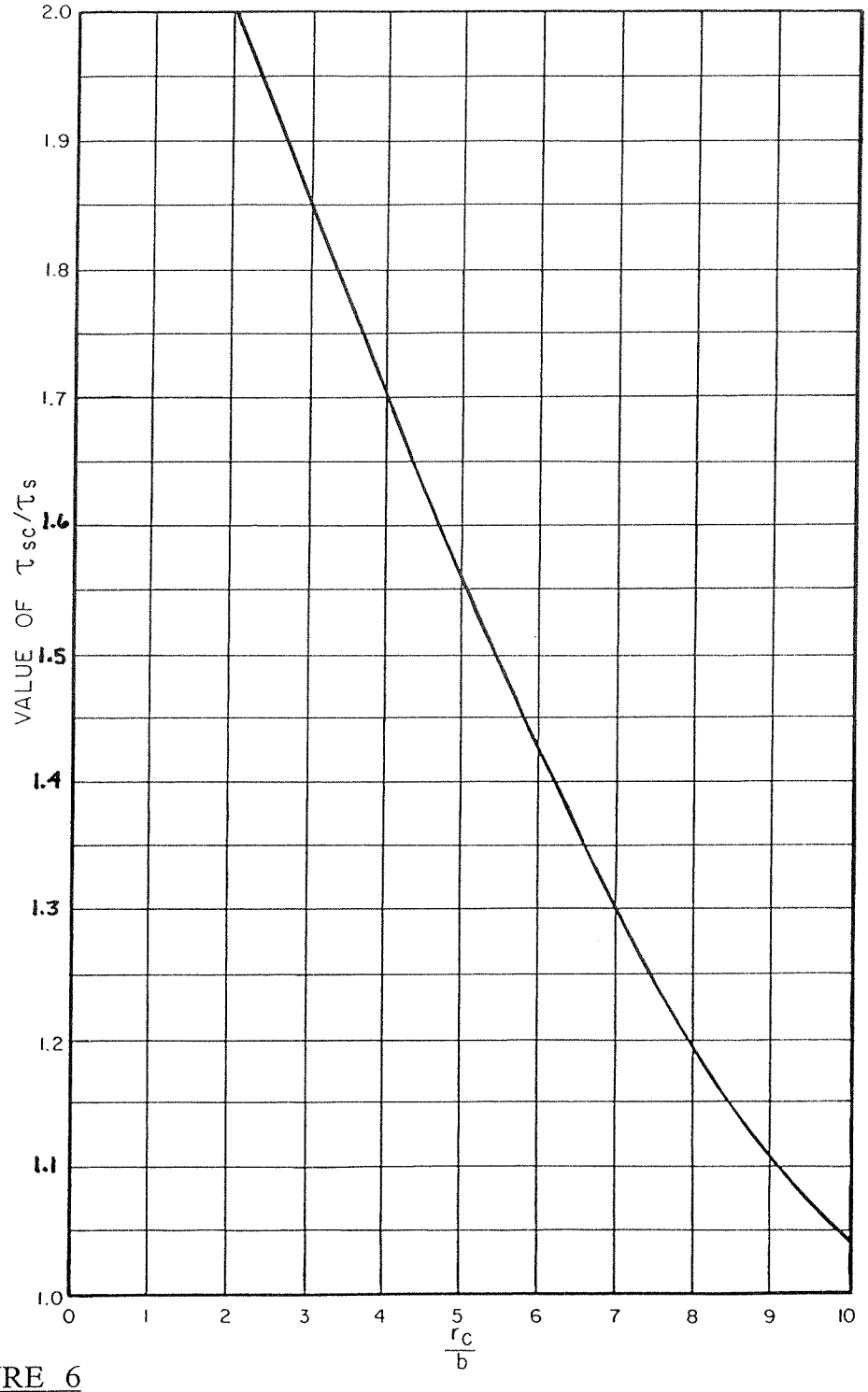


FIGURE 6

ACTUAL MAXIMUM TRACTIVE STRESS, τ_{sc}, ON SIDES OF TRAPEZOIDAL CHANNELS WITHIN A CURVED REACH

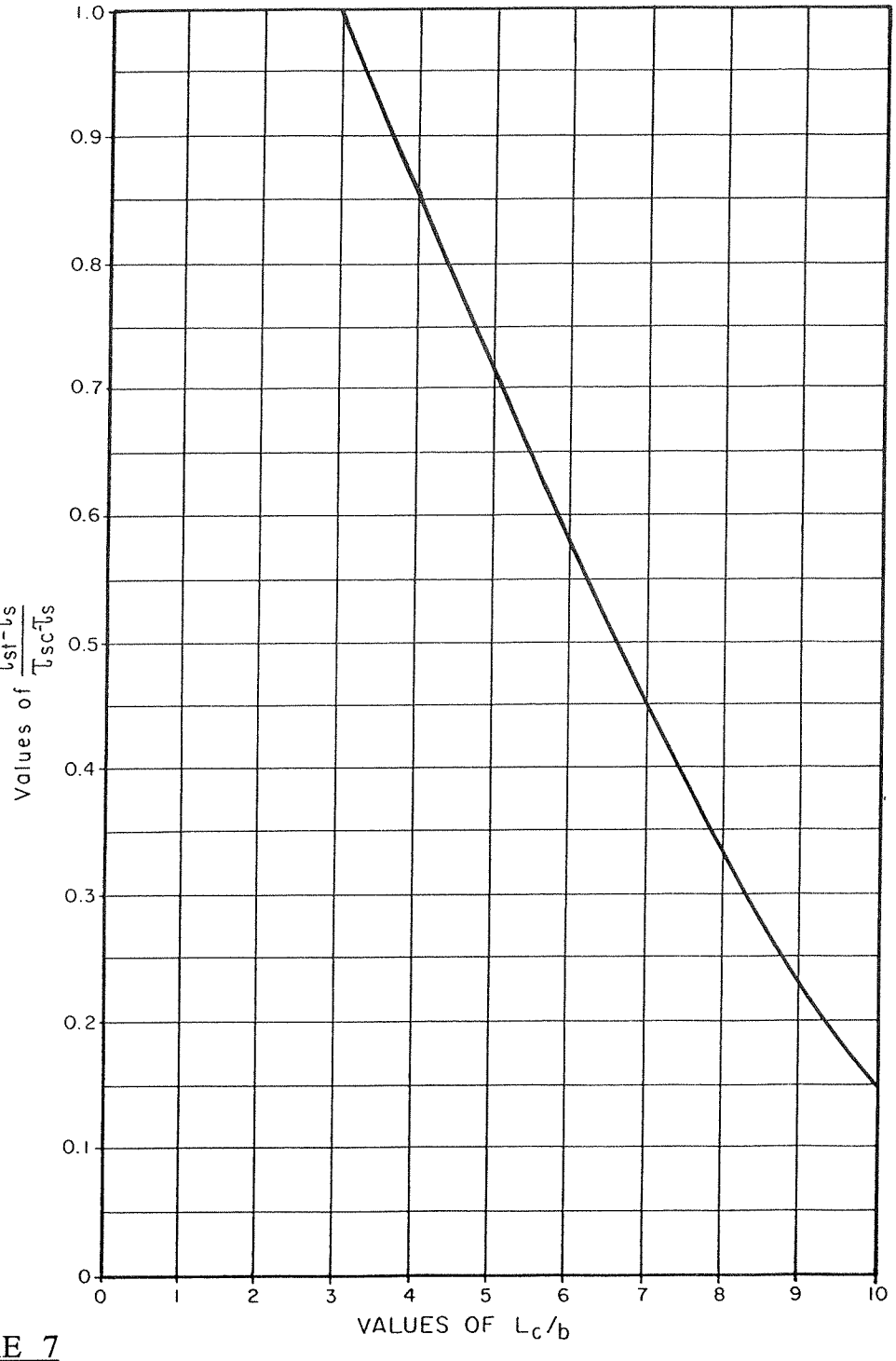


FIGURE 7

ACTUAL MAXIMUM TRACTIVE STRESS, τ_{st}, ON SIDES OF TRAPEZOIDAL CHANNELS IN STRAIGHT REACHES IMMEDIATELY DOWNSTREAM FROM CURVED REACHES

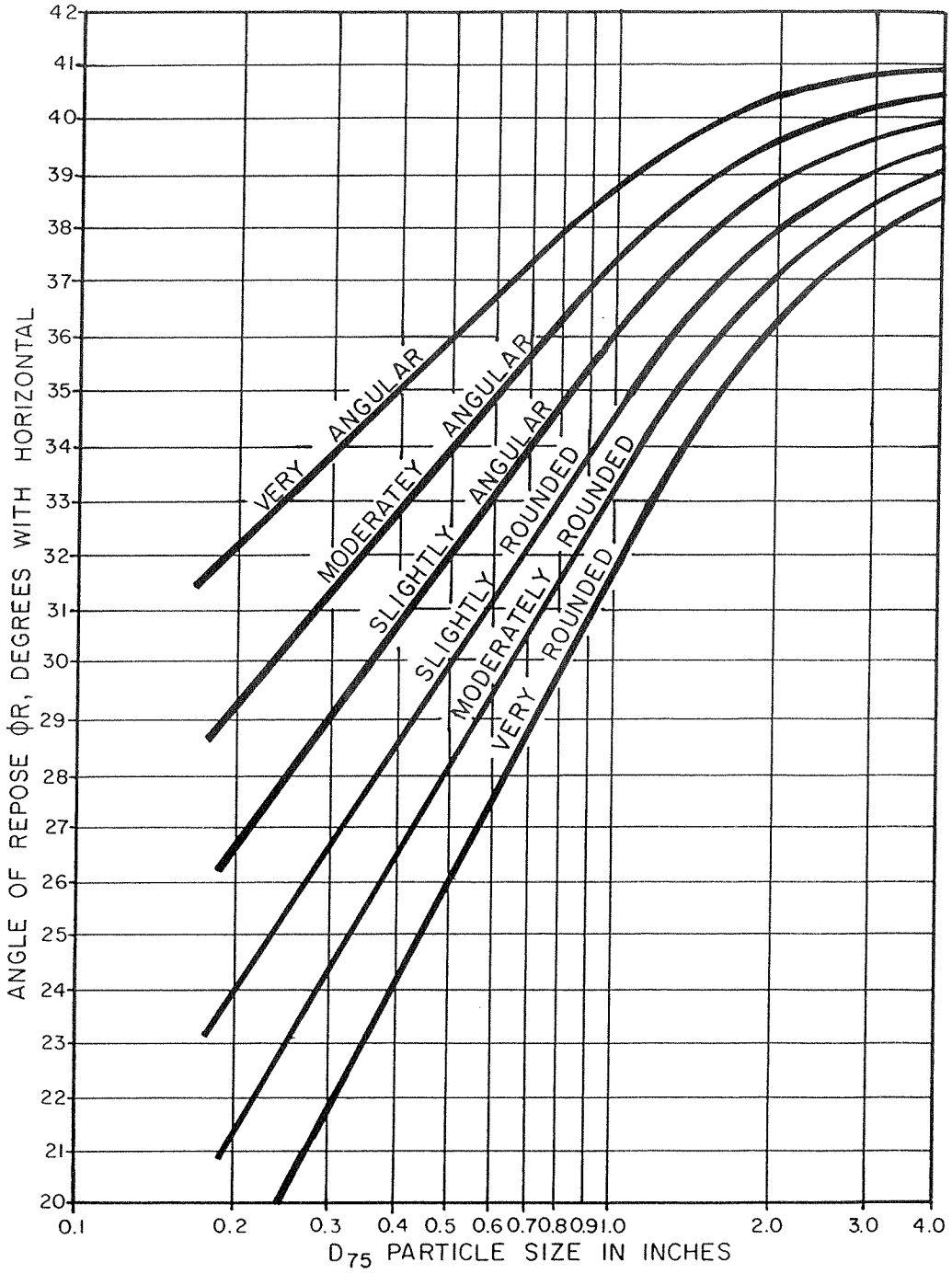


FIGURE 8

ANGLE OF REPOSE, ϕR, FOR NON-COHESIVE MATERIALS

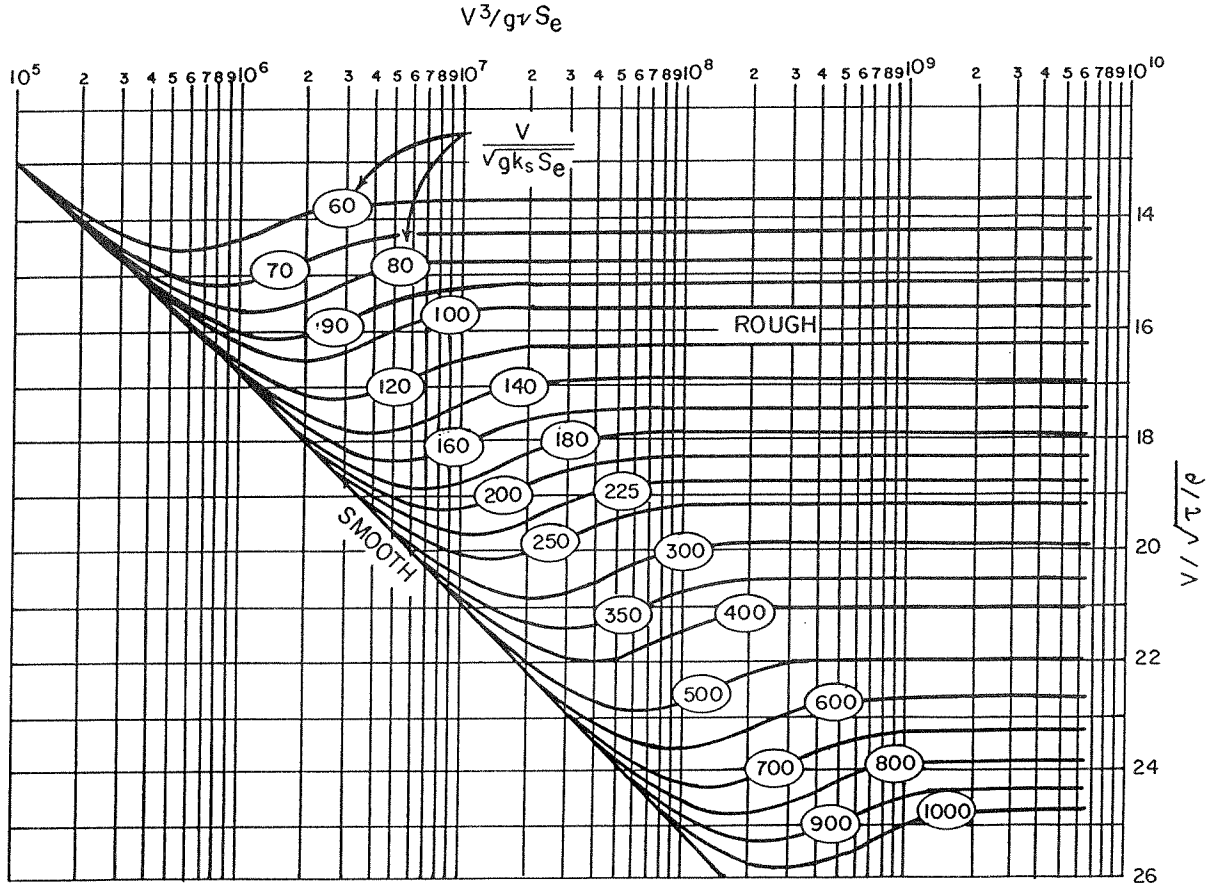


FIGURE 9

GRAPHIC SOLUTION OF REFERENCE TRACTIVE STRESS

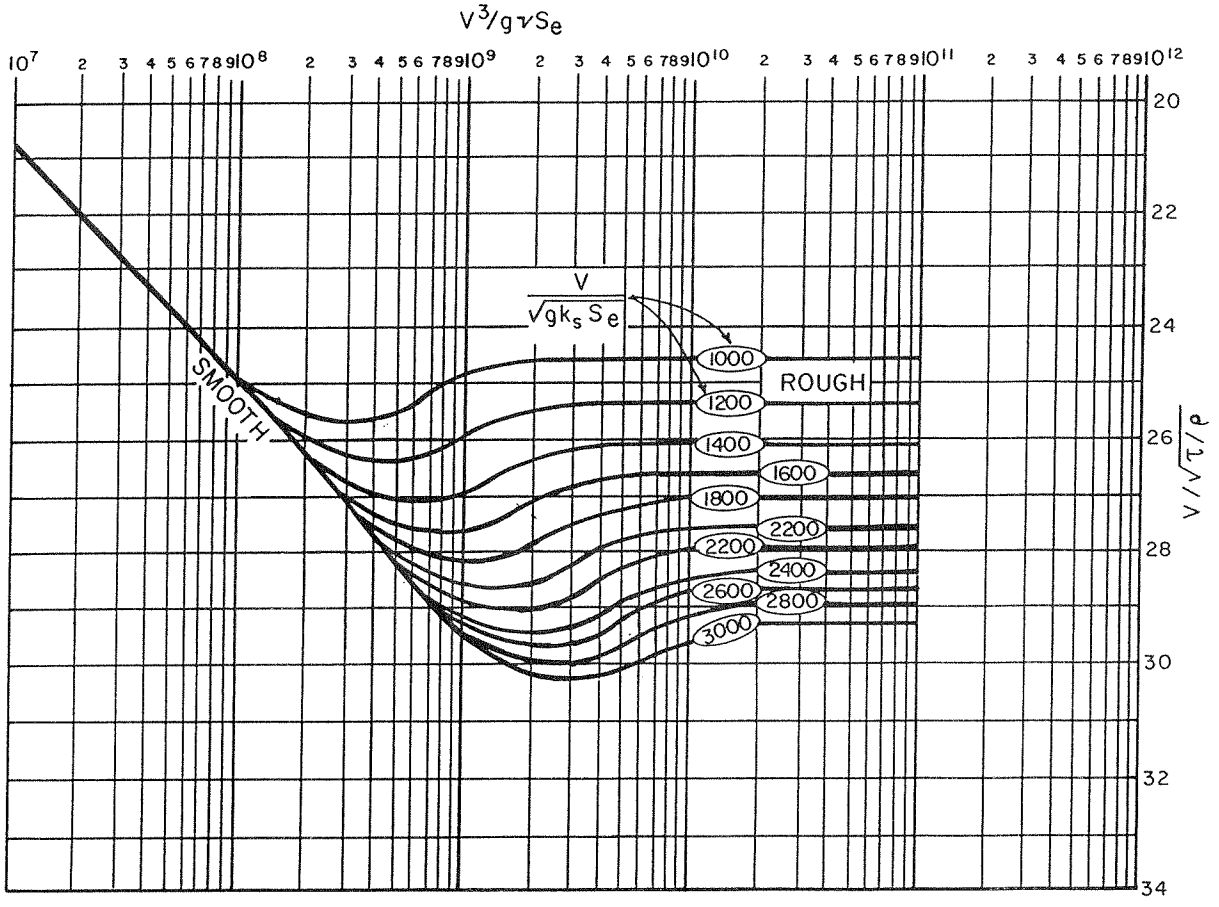


FIGURE 10

GRAPHIC SOLUTION OF REFERENCE TRACTIVE STRESS (CONTINUED)

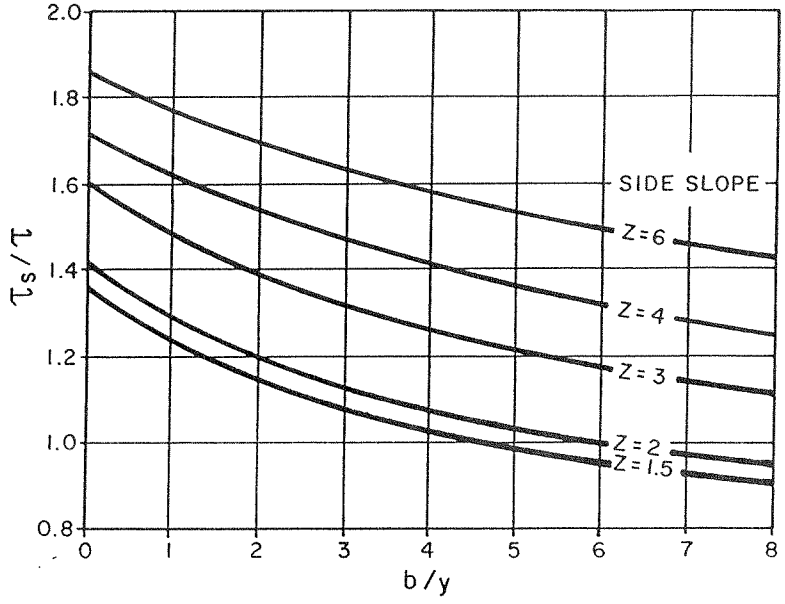


FIGURE 11

APPLIED MAXIMUM TRACTIVE STRESSES, τs, ON SIDES OF STRAIGHT TRAPEZOIDAL CHANNELS

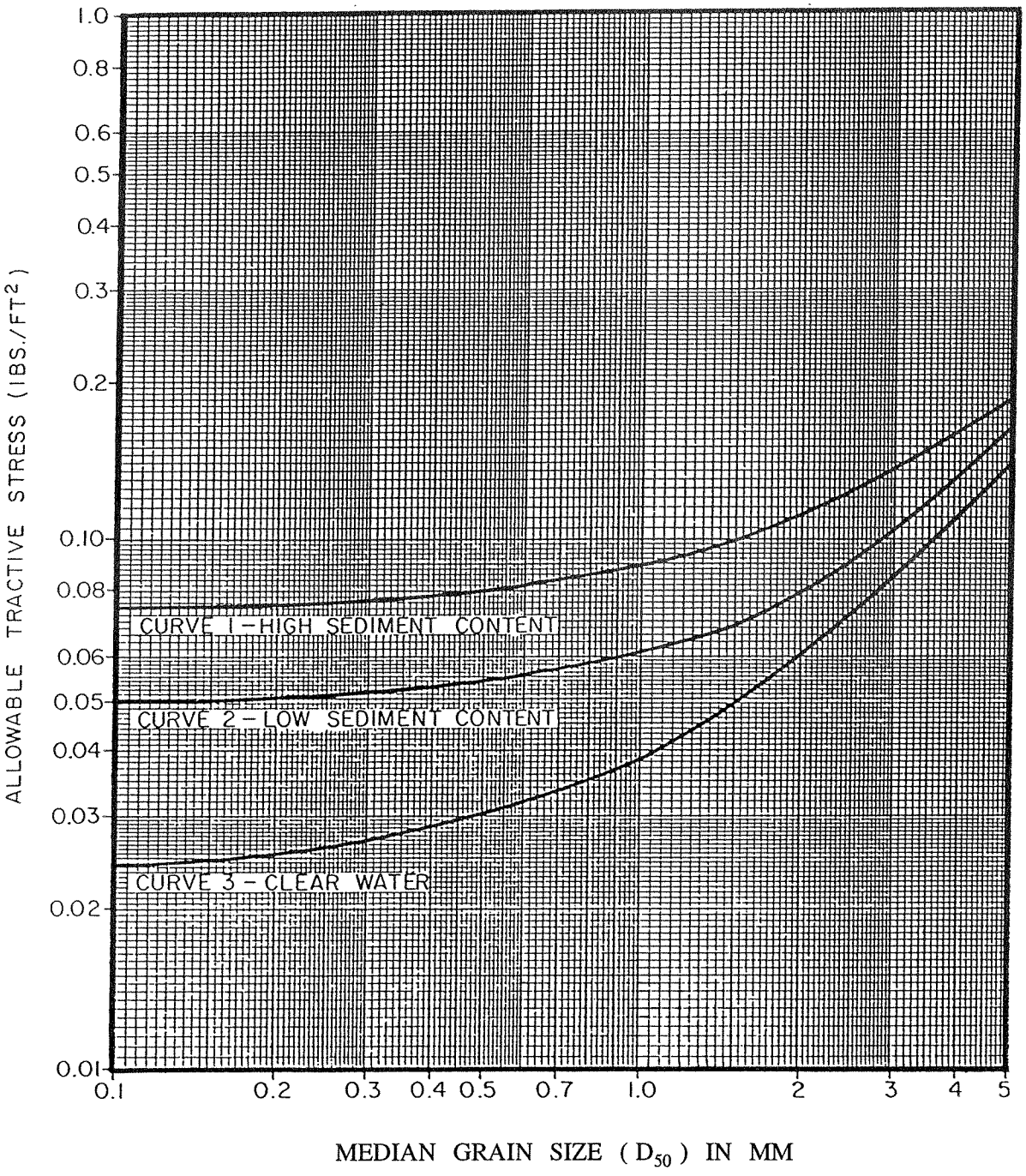


FIGURE 12

MAXIMUM ALLOWABLE TRACTIVE STRESS FOR NON-COHESIVE SOILS, $D_{75} < 0.25"$

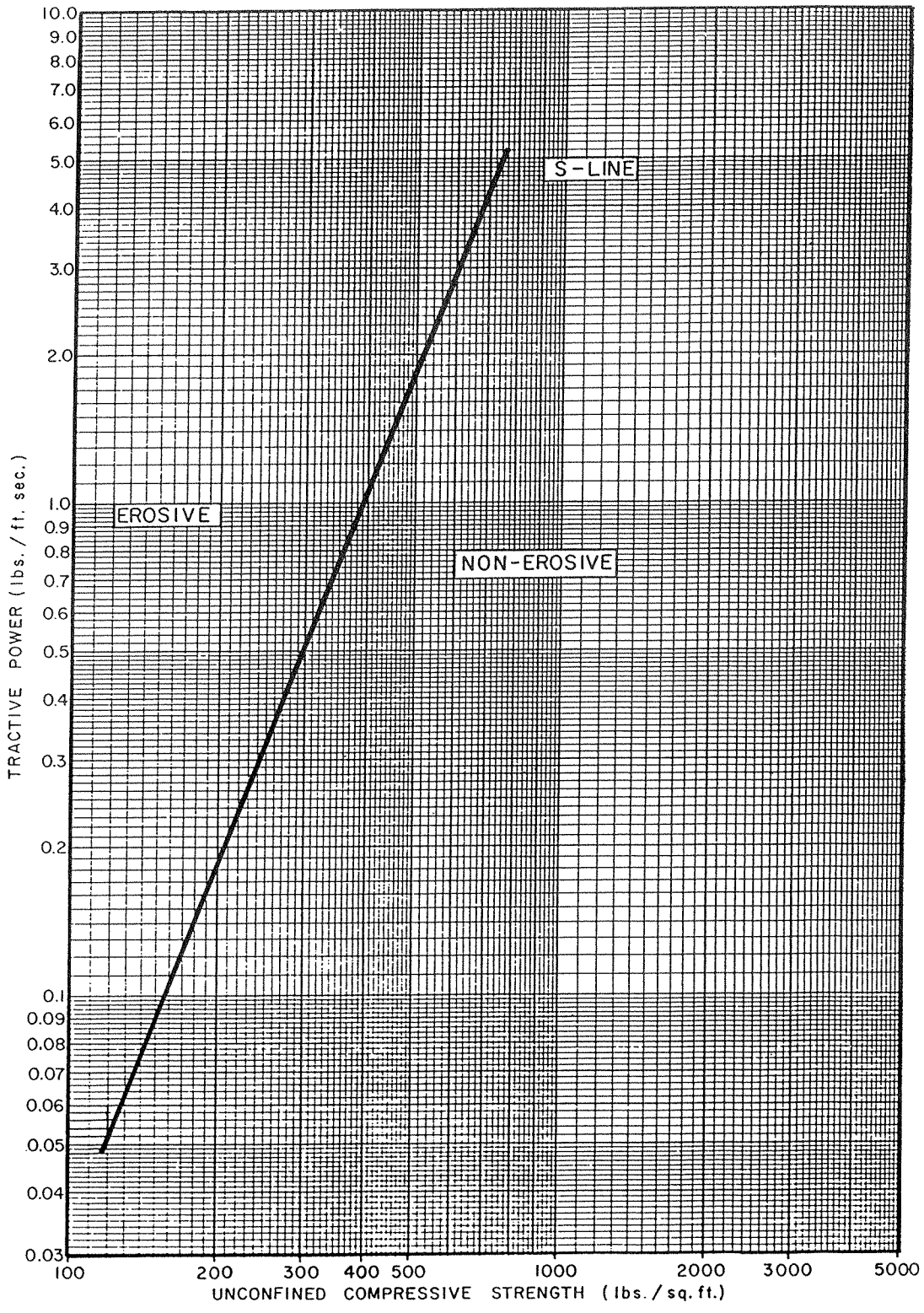


FIGURE 13

UNCONFINED COMPRESSIVE STRENGTH AND TRACTIVE POWER AS RELATED TO CHANNEL STABILITY

GUIDELINE 2

Channel Degradation Estimation for Alluvial Channels in Arizona

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Introduction

Channel degradation occurs within watercourses composed of erodible material, where local or general differentials in sediment transport capacity exist. Numerous factors control the short and long term degradation potential of channel reaches, including the size and cohesiveness of the material of which the channel is composed, the vegetation type and density in the channel, the hydraulic characteristics generated within the channel under flood events, and the existence of flow redirection or concentration structures within the channel. A key factor, however, is the amount of variation in channel properties from reach to reach. A channel reach attempts to adjust to conditions imposed on it by factors occurring up- and downstream; thus, the more uniform the channel is along the system under study, the less the potential exists for channel degradation to be a significant factor. Natural and man-made discontinuities along the system can create local increases in sediment transport potential, which often result in local degradation of the channel. System-wide disturbances, such as those associated with urbanization of the watershed or dam construction, have more far reaching impact, as the entire channel is forced to adjust to a change in sediment supply.

This document presents procedures that may be used for estimation of channel degradation in unlined watercourses within Arizona. Three levels of procedures are provided, with data requirements, procedural complexity, and accuracy of results all increasing as the analysis level is incremented. The Level I approach provides an initial estimate of local channel degradation potential for generally stable, natural channel conditions. The resulting initial estimate may be reduced through use of the more rigorous Level II methodologies. Level III procedures are outlined for situations that warrant more detailed channel degradation determination.

Procedure

General

Three levels of procedures for estimation of channel degradation depth are described in the following paragraphs. The first level of analysis provides an initial estimate of the potential scour depth to consider for design of structures to be placed near a streambed or along the banks of a channel. This first level of analysis is recommended only for channel reaches that are expected to be in general balance with the surrounding system -- i.e. no major disturbances (dams, bridges, encroachments, etc..) are evident in the site vicinity -- and where the desire is to establish a "safe" scour depth to allow for the concentration of flows that can naturally occur within channels composed of erodible material. The Level II procedures provided are methods for demonstrating the site specific limits to erosion potential, involving computations which require local hydraulic information and sediment size distributions, or historical evidence of channel performance. The third level of procedures outlined will provide more definitive determination of channel stability in the reaches under study. This level of analysis is recommended in areas where local flow characteristics are complex, where the channel has been redirected or otherwise modified by acts of man, or where the safety of local paralleling or crossing structures is of high concern.

Level I

This level of analysis requires the following information :

> Peak discharge associated with the 100-year flood (Q_{100}). May be estimated using simplified methodologies such as ADWR State Standard #2 (SS 2-96), USGS regression equations, or other appropriate local or more detailed methods.

The total scour depth, d_s, is the combination of general degradation and long term degradation and can be computed as follows:

$$d_s = d_{gs} + d_{lts}$$

where:

d_s = Total scour depth, in feet
d_{gs} = General degradation, in feet
d_{lts} = Long term degradation, in feet

General degradation can be computed as follows:

$$d_{gs} = 0.157(Q_{100})^{0.4} \quad \text{for straight channel reaches.}$$

and

$$d_{gs} = 0.219(Q_{100})^{0.4} \quad \text{for channel reaches with curvature.}$$

The second equation will give the worst-case scour for channel curvature, and is not recommended unless significant curvature is evident along the channel reach.

Long term degradation can be computed as follows:

$$d_{lts} = 0.02(Q_{100})^{0.6}$$

This equation for long term degradation should only be used when no downstream controls exist within the channel system.

The total scour depth, d_s, should be applied to the lowest point in the local cross section for determination of the elevation to which scour will occur.

For Level I, the minimum total scour depth, d_s, shall be 3 feet.

Level II

The Level II approaches presented below may be used to demonstrate the ability of the existing channel system to resist degradation, and to justify a lesser burial requirement than that computed using the Level I equations.

Erodibility evaluation

Three procedures for determination of the erodibility of local channel material under computed hydraulic conditions are presented in the ADWR's State Standard for Lateral Migration Setback Allowance for Riverine Floodplains in Arizona. These procedures are: (1) the allowable velocity approach; (2) the tractive stress approach; and, (3) the tractive power approach. One or more of these procedures can be used to demonstrate the adequacy of the material of which the channel is composed to resist the erosive action of the flow under 100 year flow conditions.

Armoring potential evaluation.

An evaluation of relative channel stability can be made by evaluating incipient motion parameters and determining armoring potential. The definition of incipient motion is based on the critical or threshold condition where hydrodynamic forces acting on a grain of sediment have reached a value that, if increased even slightly, will move the grain. Under critical conditions, or at the point of incipient motion, the hydrodynamic forces acting on the grain are just balanced by the resisting forces of the particle. For given hydrodynamic forces, or equivalently for a given discharge, incipient motion conditions will exist for a single particle size. Particles smaller than this will be transported downstream and particles equal to or larger than this will remain in place.

The Shields diagram (Figure 1) may be used to evaluate the particle size at incipient motion for a given discharge. The Shields diagram was developed through measurements of bed-load transport for various values of the Shields parameter (y axis of Figure 1) at least twice as large as the critical value, and extrapolated to the point of vanishing bed load. In the turbulent range, where most flows of practical engineering interest occur, this diagram suggests that the Shields parameter is independent of flow conditions and the following relationship is established:

$$D_c = \tau_p / [0.047 (\gamma_s - \gamma)]$$

where D_c is the diameter of the sediment particle for conditions of incipient motion, τ_p is the boundary shear stress acting on the particle, γ_s and γ are the specific weights of sediment and water, respectively, and 0.047 is a dimensionless coefficient. Any consistent set of units may be used with this equation. Typical values for γ_s and γ in English units are 165 lb/ft^3 and 62.4 lb/ft^3, respectively.

For computation of shear stress on the boundary particles, the following relations are recommended:

$$\tau_p = \tfrac{1}{8} f \rho V^2$$

$$f = 116.5\ n^2 / R^{1/3}$$

$$n = D_{90}^{1/6} / 26$$

where
- f = friction factor (dimensionless)
- ρ = density of the water
- V = flow velocity
- n = Manning resistance value
- R = hydraulic radius of the channel
- D_{90} = particle size which is larger than 90 percent of all sizes

The units of the above are as follows: τ is in lb/ft^2; ρ is in slugs/ft^3 (typically 1.94 slugs/ft^3); V is in feet per second; and R is in feet. The relation presented above relating the Manning n value to the D_{90} of the local bed material yields the resistance factor associated with the particle roughness only, and assumes D_{90} is in meters.

The shear stress computed from the above equation should be increased in areas of channel curvature using Figure 2.

The armoring process begins as the non-moving coarser particles segregate from the finer material in transport. The coarser particles are gradually worked down into the bed, where they accumulate in a sublayer. Fine bed material is leached up through this coarse sublayer to augment the material in transport. As movement continues and degradation progresses, and increasing number of non-moving particles accumulate in

the sublayer. This accumulation interferes with the leaching of fine material so that the rate of transport over the sublayer is not maintained at its former intensity. Eventually, enough coarse particles accumulate to shield, or "armor," the entire bed surface. When fines can no longer be leached from the underlying bed, degradation is arrested.

Potential for development of an armor layer can be assessed using Shields' criteria for incipient motion and a representative bed-material composition. In this case a representative bed material composition is that which is typical of the depth of anticipated degradation. Using the equation presented above, the incipient-motion particle size can be computed for a given set of hydraulic conditions. If no sediment of the computed size or larger is present in significant quantities in the bed, armoring will not occur. Armoring is probable when the particle size computed from the above equation is equal to or smaller than the D_{90} size.

After determination of the percentage of the bed material equal to or larger than the armor particle size (D_c), the depth of scour necessary to establish an armor layer (ΔZ_a) can be calculated from the following equation:

$$\Delta Z_a = y_a [(1/P_c) - 1]$$

where y_a is the thickness of the armoring layer and P_c is the decimal fraction of material coarser than the armoring size. The thickness of the armoring layer (y_a) ranges from one to three times the armor particle size (D_c), depending on the value of D_c. Field observations suggest that a relatively stable armoring conditions requires a minimum of two layers of armoring particles.

Channel profile history comparison

This procedure, applicable where sufficient data is available, relies on the historical record for indication of the degradation potential of the local channel reach. This procedure should be used to demonstrate the stable or aggrading tendency of the reach in question, rather than to estimate potential degradation depths. Given a reach of channel with successive record of channel profile changes, associated with hydrologic information for the events occurring between surveys, the reviewer can determine the trend of the channel changes and assess the likelihood of trend continuation for the future. Where the stable or aggradational trend is obvious, and no changes are anticipated in the channel system to alter the on-going trend, a lesser degradation allowance than that provided under the Level I guidelines would be reasonable.

Grade stabilization measures adequacy analysis

Grade stabilization measures of some form may be proposed or already in place which may act to limit the degradation potential of the watercourse of concern. In some areas within Arizona, procedures are in place for assessment of the adequacy of channel

stabilization measures. For areas without standardized procedures, two references are recommended which detail evaluation procedures:

Design Manual for Engineering Analysis of Fluvial Systems, Arizona Department of Water Resources, 1985.

Standards Manual for Drainage Design and Floodplain Management in Tucson, Arizona, City of Tucson Department of Transportation, Engineering Division, 1989.

Level III

This level of analysis involves modeling the hydraulic and sediment transport characteristics of the local watercourse in order to simulate the erosion/sedimentation and channel deformation processes which are expected to occur in the area of concern. For this level of analysis, Level III hydrology shall be performed to generate required hydrographs. Level III analyses should be performed by persons with knowledge and experience in the fields of sediment transport and river geomorphology. It is recommended that any movable boundary river modeling used for establishment of degradation potential be the culmination of a thorough analysis consisting of:

(1) evaluation of historical trends;
(2) qualitative analysis based on field evaluation and application of geomorphic principles;
and, (3) steady state hydraulic and sediment transport analysis.

Works Cited

Arizona Department of Water Resources, Flood Warning and Dam Safety Section, "Requirement for Floodplain Delineation in Riverine Environments - State Standard 2-96", July 1996.

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Lacey, G., "Stable Channels in Alluvium," in Proceedings of the Institution of Civil Engineers, Vol. 229, 1930.

Thomas, B.E., H.W. Hjalmarson, and S.D. Waltemeyer. "Methods for Estimating Magnitude and Frequency of Floods in the Southwestern United States." USGS Open-File Report. 1994. 93-419

Example Application

Example 1: Proposed Siphon Crossing of an Earthen Channel

- **Problem Statement.** A natural earthen channel traverses a site where an irrigation channel is being constructed. The watershed contributing to the earthen channel upstream of the site is 700 acres in area. A siphon is proposed to convey irrigation water across the channel.

- **Objective.** Determine the burial depth for the proposed siphon.

Level I Analysis

A 100-year peak discharge value of 530 cfs was determined from local hydrology methodology. The channel in the site vicinity has 2:1 side slopes and a bottom width of 15 feet. The proposed crossing site is at a mild bend in the channel. A sieve analysis of the local bed material yields a median grain size D_{50} = 1.0 mm = 0.0033 feet.

Calculations:

General degradation, $d_{gs} = 0.157(530)^{0.4} = 1.93$ feet

Long term degradation, $d_{lts} = 0.02(530)^{0.6} = 0.86$ feet

Total scour, d_s = 1.93 feet + 0.86 feet = 2.79 feet

Since the total scour calculated is less than the recommended minimum of 3 feet, use a total scour depth of 3.0 feet.

Level II Analysis

Further evaluation is desired to investigate the potential for reducing the burial depth indicated through application of the Level I procedure. Although no historical data is available for determination of the local aggradation/degradation trends of the earthen channel, the erodibility and armoring potential of the existing channel material can be checked using the recommended Level II procedures. The site specific hydraulic and grain size information is collected to check if erosion of the channel would be naturally limited. The channel slope in the site vicinity is estimated from USGS quadrangle maps at 0.010 feet/foot, and the Manning n value for total channel resistance is estimated at 0.030.

Using normal depth procedures, the hydraulic characteristics of the local channel under 100-year flood conditions are determined:

Flow Depth = 3.0 feet
Flow Velocity = 8.4 feet/second

The sieve analysis of the local channel material sample yields the following information:

D_{90} = 55 mm = 0.180 ft = 0.217 inches
D_{75} = 4 mm = 0.013 ft = 0.16 inches
D_{65} = 1.9 mm = 0.0062 ft = 0.07 inches

Calculations:

Erodibility Evaluation (using procedures and figures provided in Attachment 1 to this State Standard)

(1) Allowable velocity approach, assuming sediment laden flow

Entering Figure 1 with D_{75} = 4 mm yields a basic velocity of 4.0 ft/sec.

In this case, we are concerned with erosion of the channel invert in a reach containing only a mild bend, so the correction factors for channel curvature reduces to 1.0. The correction factor for side slope, which must be considered for evaluating the erodibility of the channel banks, is not applied in this case.

Entering Figure 4 with Depth = 3.0 feet yields C_c = 1.01

Maximum allowable velocity = (4.0)(1.0)(1.01) = 4.0 ft/sec

Since the computed velocity of 8.4 ft/sec exceeds the maximum allowable velocity, erosion may be expected to occur.

(2) Tractive stress approach

Since D_{75} is less than 0.25 inches, the reference tractive stress method is used;

Assuming a water temperature of 60° F, the kinematic viscosity (ν) = 0.0000121 ft^2/sec, and the density (ρ) = 1.94 $slugs/ft^3$

Compute $V^3/(g\nu S_e) = 1.52 \times 10^8$

Compute $V/(gD_{65}S_c)^{1/2} = 188$

From Figure 9, $V/(\tau/\rho)^{1/2} = 18.2$

Solving the above equation yields $\tau = 0.41$ lb/ft^2.

No correction factor for side slope is applied, and the correction factor for channel curvature reduces to 1.0 for a mild bend.

From Figure 12, Curve 1 (for high sediment content), the allowable tractive force is 0.09 lb/ft^2. Since 0.09 is less than 0.41, the channel is erosive.

(3) Tractive power approach

An unconfined compressive strength (UCS) test of the saturated channel soils is performed, yielding a strength of 800 lb/ft^3.

Assuming half of this strength for design purposes, UCS_{design} = 400 lb/ft^3.

Compute tractive power = $V\tau_s = 3.44$

From Figure 13, the condition falls above the S-Line, indicating that the channel is erosive.

Armoring potential evaluation

Manning's n related to particle roughness = $[55/1000]^{1/6} / 26 = 0.024$

Channel flow area = $[15+2(3.0)](3.0) = 63.0$ square feet

Channel wetted perimeter = $15 + 2(3.0)(5)^{1/2} = 28.4$ feet

Hydraulic Radius = $63.0/28.4 = 2.22$ feet

Friction factor = $f = 116.5\ (0.024)^2 / (2.22)^{1/3} = 0.051$

Particle shear stress = $\tau_p = \frac{1}{8}\ (0.051)(1.94)(8.4)^2 = 0.87$ lb/ft^2

Critical particle size = $D_c = .87/[0.047(165-62.4)] = 0.18$ feet = 54.9 mm

Since the critical particle size is essentially equal to D_{50}, armoring is a possibility.

Therefore, the percent of material greater than D_c = 54.9 mm is 10%

Armor thickness = $y_a = 2D_c$ = 0.36 feet

Depth of degradation required for armoring to form:

$$\Delta Z_a = y_a [(1/P_c) - 1] = 0.36[(1/0.10) -1] = 3.24 \text{ feet}$$

Since the depth required for armoring to occur exceeds the Level I burial depth, armoring will not control, and the recommended burial depth is the minimum allowable value of 3.0 feet.

Level III Analysis

The conclusions derived from the Level II analysis and the nature of the problem indicate that the Level III analysis would probably not be applied in this case. However, should the designer wish to proceed with the degradation investigation, a registered engineer with experience in sediment transport modeling could be employed for this purpose. The engineer would be expected to collect available historic information, document the historic planform changes to the watercourse under events of varying frequency, apply steady state hydraulic and sediment transport calculation procedures to determine the erosion/sedimentation characteristics of the local reach of channel, and, potentially apply a moveable boundary river simulation model to quantify the changes likely along the study reach under design event conditions.

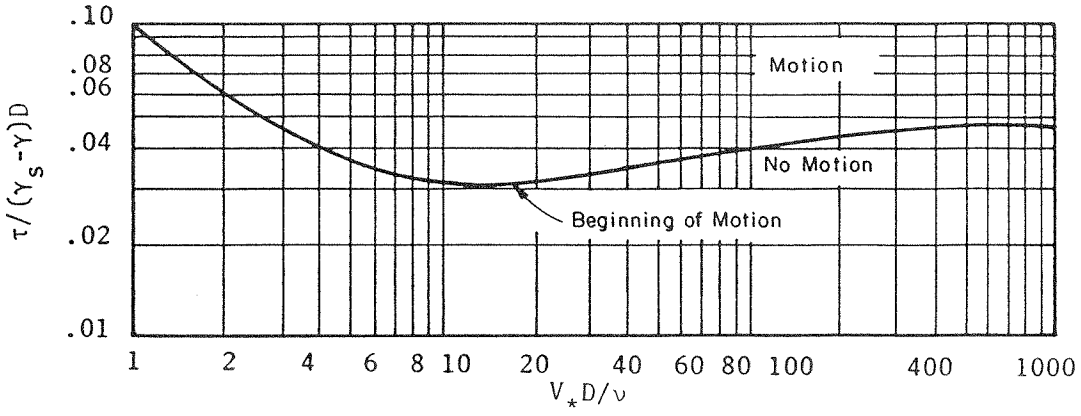

FIGURE 1

SHIELD'S RELATION FOR BEGINNING OF MOTION

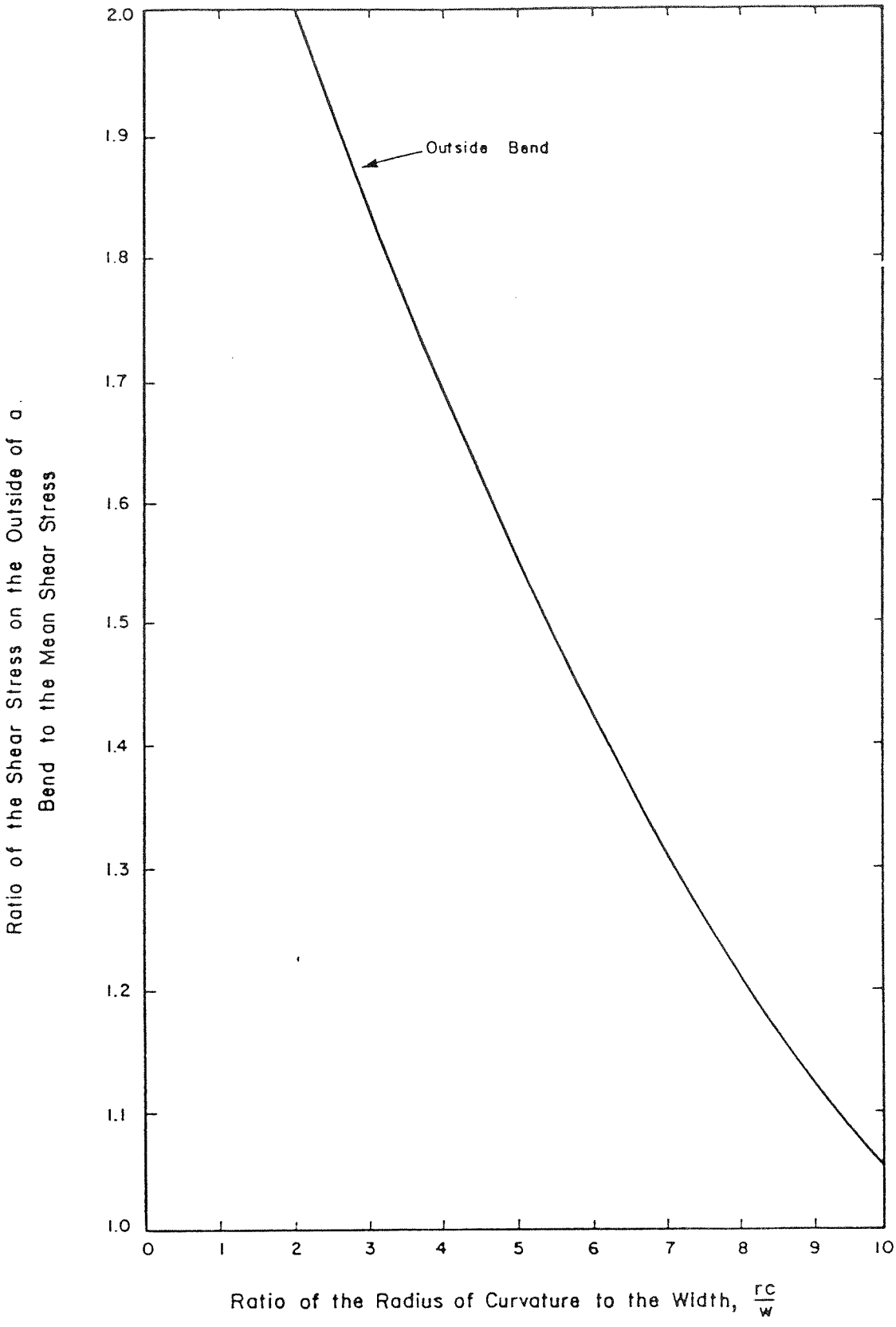

FIGURE 2
EFFECT OF BEND ON BOUNDARY SHEAR STRESS

GUIDELINE 3

Evaluation of River Stability Impacts associated with Sand and Gravel Mining

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Introduction

The river stability impacts associated with instream or near-stream sand and gravel operations depend on the local watershed and river characteristics, and on the mining and management practices followed. Excessive sand and gravel removal from a river channel can endanger the stability of the river system by inducing general scour and headcutting. These processes can undermine the burial and/or support materials for facilities that cross or parallel the watercourse, increasing the likelihood of structure failure. These processes can also increase the rate of erosion of a dike or buffer zone designed to separate a near-river pit from an active river channel. A headcut and erosion through such a buffer zone could alter local river channel characteristics and transport rates, and impact both upstream and downstream reaches. If the channel reach adjacent to a floodplain mining pit is geomorphically active (e.g., migrating laterally), the same result might occur if protective measures or an adequate buffer zone are not provided during site development.

The scour and deposition problems associated with sand and gravel mining are very complicated. The dominant physical processes include water runoff, sediment transport, sediment routing, degradation, aggradation, and breaking and forming of the armor layer. These processes are unsteady and complicated in nature. Furthermore, each situation is unique and requires independent analysis. No standard equation or formula can be adopted which is universally applicable to all gravel mining evaluations. However, general guidelines have been developed for determination of the adequacy of buffer areas between proposed mining operations and active river channels, and procedures are available for analysis of the effects of instream activities.

Procedure

General

This document presents three levels of procedures that may be applied for evaluation of sand and gravel operations in areas adjacent to or within watercourses. The first level procedure may be applied to estimate the size of an adequate erosion buffer area between an active river channel and a near-stream operation. The second level procedure may be used to investigate the erosion resistance of buffer materials, in cases where the applicant desires to reduce the buffer area developed using the Level 1 procedures. A third level procedure is presented to enable more definitive determination of the erosional/depositional tendencies of a channel adjacent to a near-stream mining site, or to determine the potential impacts of instream mining operations.

The aggradation/degradation trends of river reach that contains or is adjacent to a sand and gravel mining operation are governed by the same processes that act on an unmined reach -- differentials in sediment transport capacities and sediment supply result in degradation in areas of deficit and aggradation in areas of surplus. The potential hazard associated with sand and gravel mining operations in the vicinity of watercourses may be evaluated using the same procedures as those described in the Channel Degradation and Lateral Migration portions of this State Standard. The mining area is analyzed either as a particular portion of the river (for the case of an instream site), or as an off-channel development (for an operation established adjacent to a river's banks).

For mining operations that are to be established outside of the floodplain, the Level I, II, or III techniques detailed in the Lateral Migration guideline would apply. Instream operations, however, require the application of more rigorous procedures. The mining area is separated into subreaches of similar geometry and hydraulics (i.e., (1) the reach upstream of the mining area, (2) the upstream slope down into the pit, (3) the pit itself, and (4) the reach immediately downstream of the pit), and analyzed using river modeling procedures.

The recommended approaches for evaluation of sand and gravel mining operations in the vicinity of watercourses are summarized below:

Level I

Estimate of the required buffer distance between a near-stream site and the active channel.

Setback the top of the proposed mining pit a distance from the floodplain given by the Level I setback criteria (as detailed in the Lateral Migration Guidelines).

Level II

Evaluation of the erodibility of the buffer materials for minimization of near-stream site setback requirements.

Require a smaller setback from the floodplain boundary if justified by application of the Level II setback criteria (as detailed in the Lateral Migration Guidelines).

Level III

Mathematical modeling of the river channel to better determine the adequacy of the buffer provided for a near-stream operation or to quantify the river stability impacts associated with an instream operation.

Use steady state or movable boundary sediment transport analysis (backed up by qualitative analysis and historical evidence) to determine the short and long term impact of proposed mining operation, including headcut impacts and downstream impacts due to sediment deficit. For this level of analysis, Level III hydrology shall be performed to generate required hydrographs. Level III analyses should be performed by persons with knowledge and experience in the fields of sediment transport and river geomorphology. It is recommended that any movable boundary river modeling used for determination of lateral channel stability or for evaluation of instream mining impacts be the culmination of a thorough analysis consisting of:

(1) evaluation of historical trends;
(2) qualitative analysis based on field evaluation and application of geomorphic principles;
and, (3) steady state hydraulic and sediment transport analysis.