SOME ASPECTS OF
GULLY DEVELOPMENT, CLASSIFICATION AND CONTROL

Thesis by

N. A. Christensen

In Partial Fulfillment of Requirements
for the
Degree of Doctor of Philosophy

California Institute of Technology
Pasadena, California
1938

ABSTRACT

The various types of gully cross-sections are described and shown to be dependent upon the relative importance of down-scour, side-scour and bank degradation, and it is shown that the type of the mean cross-section is determined by the dominant one of these three processes. Not only is the relative importance of the developmental process indicated by the mean cross-section, but also the stage of development of the gully. A means by which the stage of development may be ascertained is important because it is the first step in selecting the best method of treatment.

A discussion of the forces underlying the developmental processes is given, and the conditions for complete stability are indicated.

The effects of grade reduction, stream sorting, and sediment load upon the development of gullies are deduced. The artificial treatments by man are discussed in the light of these deductions.

A method for reclaiming major gullies, which are in the early stages of development, is given.

SOME ASPECTS OF
GULLY DEVELOPMENT, CLASSIFICATION AND CONTROL

By Nephi A. Christensen

INTRODUCTION

a major problem confronting soil conservationists is the control of deep gullies characterized by caving banks. Gullies of this type often entrench themselves 50 feet or more, and have almost vertical banks which can not be protected permanently with a cover of vegetation. Such gullies not only baffle farmers whose land they traverse, but also present difficult problems to technical experts who must devise means for their control. It seems a simple premise that an adequate method of control must be based upon a knowledge of the processes at work.

In this paper the various possible types of gully cross-sections are described and shown to depend upon the relative importance of the three processes causing gully development. These processes which are down-scour, side-scour and bank degradation are defined and clearly differentiated. It is shown that the type of the mean cross section is determined by that process which is dominant. And it is further shown that the mean cross section, in turn, indicates the stage of development and gives a basis for selecting appropriate means of control.

At present the basic knowledge is too meager to insure the correct answer to such questions as : When is vegetation suitable for control? When are structures necessary? Under what conditions should the flow be diverted from the gylly? Is reclamation practical, and if so, when? Will present methods remain adequate and prove to be the most economical over a long period of time?

It is hoped that the presentation and discussion of basic principles in this paper will make gully classification possible and help to indicate the best methods of control.

TYPES OF GULLY CROSS-SECTIONS

Three processes affect the development and character of gully cross-sections: first, scour of the stream bottom; second, scour of the stream banks ("stream" denotes a concentrated flow of water regardless of size and continuousness.); and third, washing and sloughing of the gully banks caused by rain, frost action and drying, exclusive of caving due to undermining by the stream. This third process will hereafter be called bank degradation. In any gully all of these processes are at work and the character of the gully section is dependent upon which of the three is dominant. The meaning of dominance will be more fully developed below. For the present, the general characteristics of gully cross-sections which result when each of these three processes is dominant will be described.

The first type to be considered is that in which down-scour is dominant. In Figure 1, the three general types are represented idealistically. The following symbols used in these sketches are defined at the bottom of the figure:

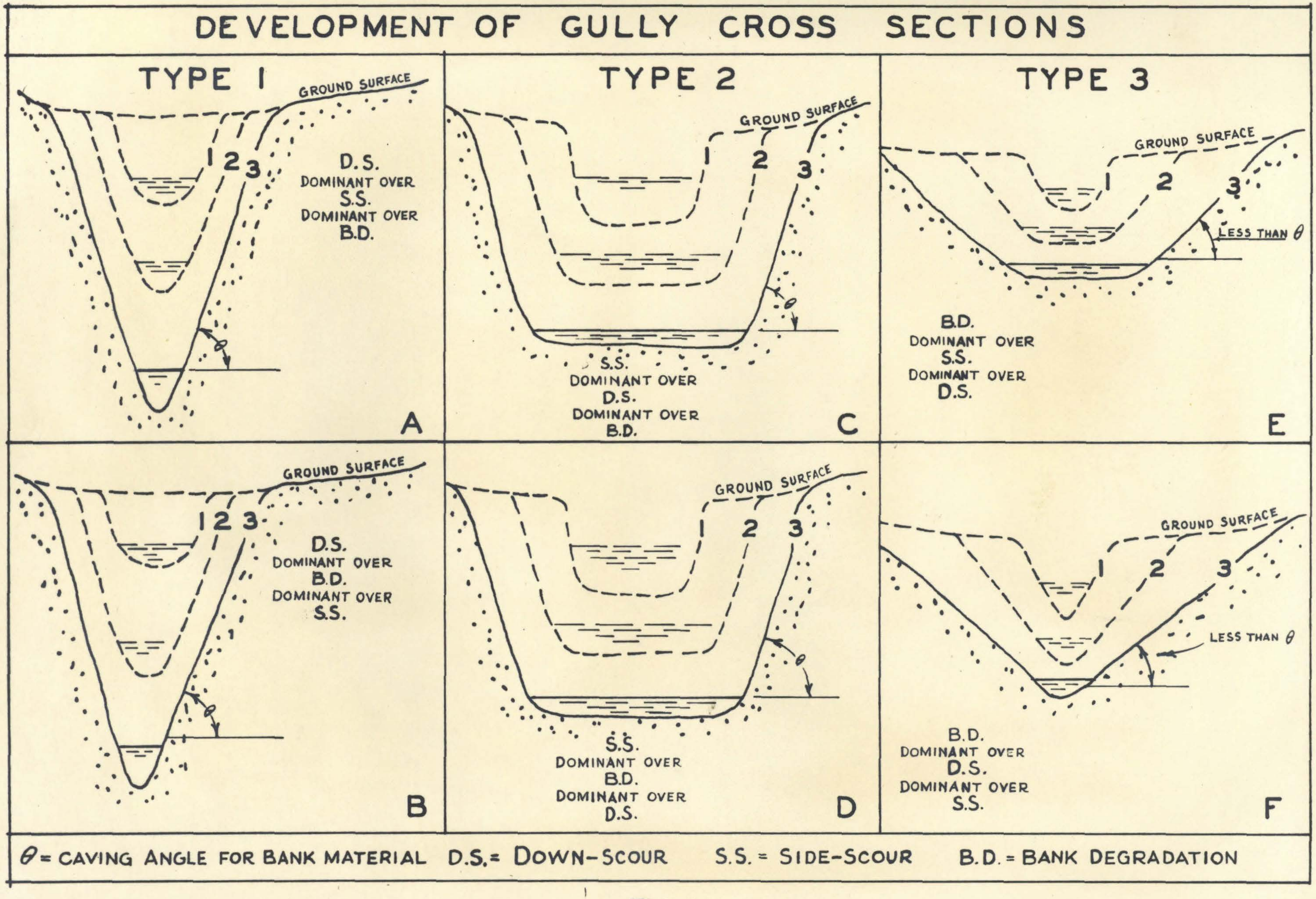

DEVELOPMENT OF GULLY CROSS SECTIONS
TYPE 1
TYPE 2
TYPE 3
GROUND SURFACE
1 2 3
θ
D.S. DOMINANT OVER S.S. DOMINANT OVER B.D.
A
S.S. DOMINANT OVER D.S. DOMINANT OVER B.D.
C
LESS THAN θ
B.D. DOMINANT OVER S.S. DOMINANT OVER D.S.
E
D.S. DOMINANT OVER B.D. DOMINANT OVER S.S.
B
S.S. DOMINANT OVER B.D. DOMINANT OVER D.S.
D
B.D. DOMINANT OVER D.S. DOMINANT OVER S.S.
F
θ = CAVING ANGLE FOR BANK MATERIAL
D.S. = DOWN-SCOUR
S.S. = SIDE-SCOUR
B.D. = BANK DEGRADATION

FIG. 1

θ represents the caving angle of the bank material.

DS represents the down-scour by the stream.

SS represents the side-scour by the stream.

BD represents bank degradation.

Figure 1a indicates three successive stages in the development of the gully cross-section where down-scour is dominant over side-scour which, in turn, is dominant over bank degradation. According to the concept of dominance presented later, the width of the flow cross-section will decrease so long as down-scour dominates side-scour. In Figure 1b, the case is represented in which down-scour is dominant over bank degradation and the latter, in turn, over side-scour. The character of this cross-section is the same as represented in Figure 1a, and both shall be referred to hereafter as sections of Type 1. This type is characterized by its V-shape and caving banks.

A second type is produced when side-scour is dominant. Figures 1c and 1d represent the two possible cases of side-scour dominance. In each the character of the cross-section is the same, and they will be referred to hereafter as Type 2. These are characterized by their truncated-V shape, caving banks, and widening streambed.

The third typw results from the dominance of bank degradation. When bank degradation is dominant over side-scour which, in turn, dominates down-scour, the result is represented in Figure 1e. In this case the stream-bed will widen, the slopes of the gully banks will become flatter, and the gully cross-section will be a truncated V. The other possible case where the order of dominance is bank degradation, down-scour, and side-scour, is represented in Figure 1f.

Here the stream will widen only slightly, the slopes of the banks will become flatter, and the cross-section will be a V. Because of the fact that almost no caving of the banks takes place, vegetation will be able to maintain itself on the side slopes providing moisture is adequate and other conditions favorable. As indicated by Figures 1e and 1f, it is possible to get two shapes for the cross-section; both of these, however, will be grouped together and considered as Type 3. Sections of this type are characterized by the absence of caving due to undermining, and by bank slopes on which vegetation is usually found.

DETAILED CONSIDERATION OF DOWN-SCOUR, SIDE-SCOUR, BANK DEGRADATION, AND WHAT DETERMINES DOMINANCE

Definitions of down-scour and side-scour should be consistent with the following conditions:

1. On horizontal elements of the bed all scour is down-scour.
2. On vertical elements all scour is side-scour.
3. On sloping elements the scour normal to the bed is composed partly of down-scour and partly of side-scour.

In order to satisfy these 3 conditions, we must think of the actual rate of scour at any point as being normal to the scoured surface (S_n Figure 2a). Rate of down-scour and side-scour are components of the actual rate of scour and are represented respectively by S_y and S_x in Figure 2a.

SIDE-SCOUR, DOWN-SCOUR AND DOMINANCE

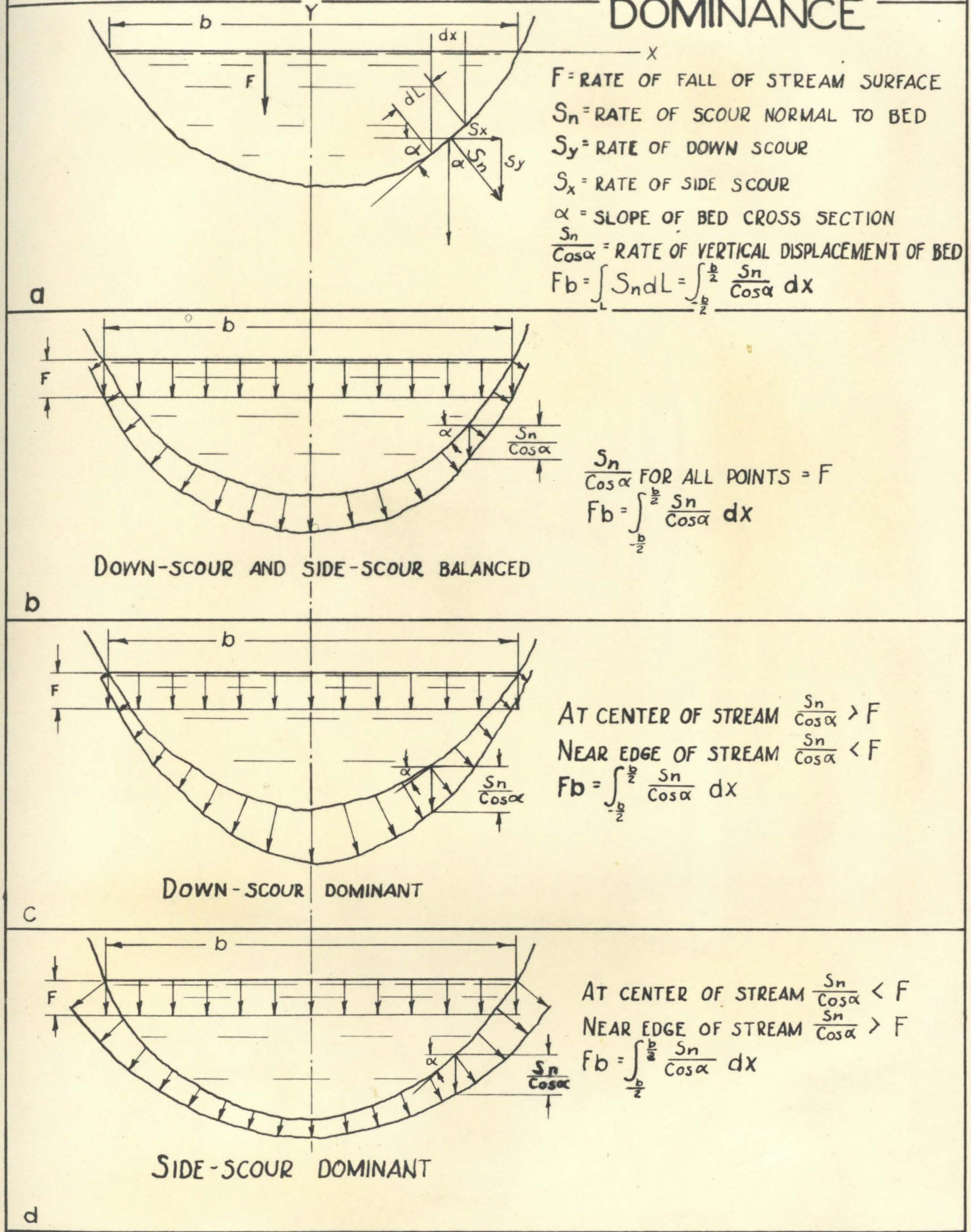


FIG. 2

$$S_y = S_n \cos\alpha$$
$$S_x = S_n \sin\alpha \qquad 1.$$

On a horizontal element i.e., $\alpha = 0^\circ$

$$S_y = S_n$$
$$S_x = 0$$

On a vertical element i.e., $\alpha = 90^\circ$

$$S_y = 0$$
$$S_x = S_n$$

The first 3 conditions are thus fulfilled.

It seems that a proper definition of dominance should recognize the following facts.

1. The stream section will deepen when down-scour is dominant.
2. The stream section will widen when side-scour is dominant.

The conditions of scour necessary to cause the stream width to change will now be discussed. As scouring by a constant flow proceeds the surface of the water must fall, this rate of fall (F) multiplied by the surface width (b) will be the total rate of scour.

Total rate of scour = Fb (area per unit time)

The total rate of scour can also be expressed as an integration thus:

$$\text{Total rate of scour} = \int_L S_n \, dL$$

but $dL = \frac{dx}{\cos\alpha}$

so

$$\text{Total rate of scour} = \int_{-\frac{b}{2}}^{\frac{b}{2}} S_n \frac{dx}{\cos\alpha} = \int_{-\frac{b}{2}}^{\frac{b}{2}} \frac{S_n}{\cos\alpha} \, dx$$

Setting these expressions equal gives

$$Fb = \int_{-\frac{b}{2}}^{\frac{b}{2}} \frac{S_n}{\cos\alpha}\, dx \qquad 2.$$

If $\frac{S_n}{\cos\alpha}$ is a constant, Equation 2 reduces to

$$Fb = \frac{S_n}{\cos\alpha} \int_{-\frac{b}{2}}^{\frac{b}{2}} dx = \frac{S_n}{\cos\alpha}\, b$$

or

$$F = \frac{S_n}{\cos\alpha} \qquad 3.$$

By substituting from Equation 3 into Equation 1

$$S_y = F \cos^2\alpha$$

$$S_x = F \cos\alpha \sin\alpha \qquad 4.$$

Equations 4 give the relation that exists when the stream cuts vertically. The vertical displacement of the stream-bed will everywhere be the same and equal to the displacement of the stream surface, as shown in Figure 2b. In this case the stream neither widens nor narrows. In this paper such a condition is considered as one of balance between down-scour and side-scour.

Now suppose that instead of $\frac{S_n}{\cos\alpha}$ being constant it decreases with an increase in α, i.e. the rate of vertical displacement of the bed is largest on horizontal elements near the center and smallest for the elements of greatest slope near the bank. (Figure 2c) But by Equation 2 the rate of generation of area by the water surface line must be equal to the total rate of scour. In order for these two conditions to hold simultaneously the rate of vertical displacement at the center ($\frac{S_n}{\cos\alpha}$) is greater than the rate of fall of the water surface while at the sides the reverse is true. (Figure 2c) Therefore, the cross section of the flow grows deeper and narrower.

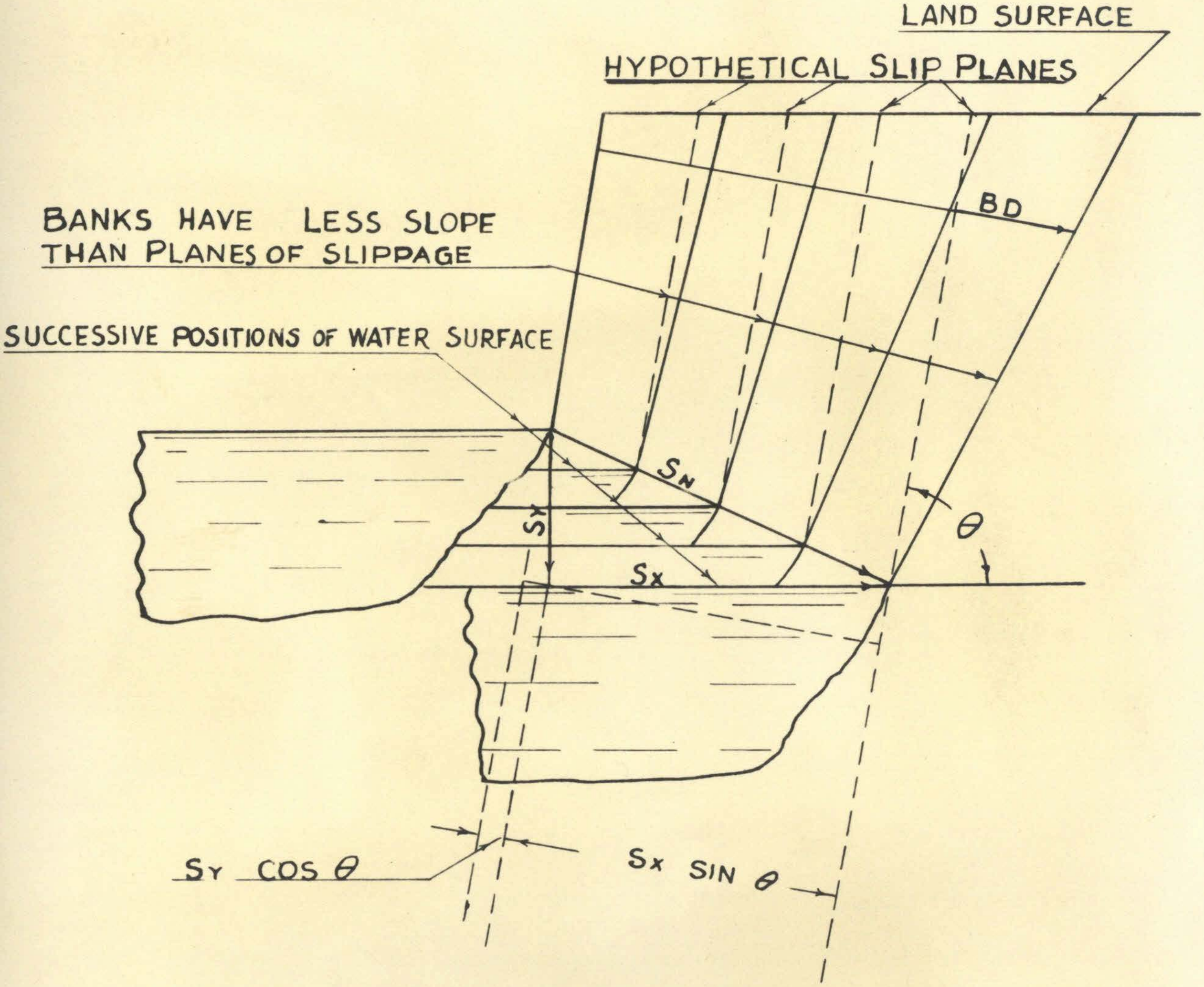
Figure 2d represents a case of side-scour dominance. Here the scour normal to the surface (S_n) is such as to give greater rates of vertical displacement near the stream edges than at the stream center. This, in turn, requires that the bed displacements at the center and sides are respectively smaller and greater than the fall of the water surface. The flow section will therefore widen and become shallower.

Attention is called specifically to the fact that the above distinction between these cases of dominance is not consistent with the meanings commonly given to the terms "down-scouring" and "side-scouring". For instance, the case in which a stream is cutting down without changing its flow section is usually thought of as being one of down-scouring exclusively, but is considered here as representing a condition of balance between the two processes. Even though this concept is somewhat at variance with common usage, it is necessary in order to make possible a consistent inclusion of all variations of scouring phenomena. By virtue of this concept, also, the gully section type takes on definite significance in relation to the developmental processes which, contrary to common beliefs, are actually continuous and coexistent and may now be so recognized.

In order to define the condition under which bank degradation is dominant, consider the bank of the gully to be composed of layers separated by slip planes as in Figure 2e. Bank degradation is dominant

BANK DEGRADATION DOMINANCE

$$BD > (S_Y \cos\theta + S_X \sin\theta)_{MAX.}$$



BD = RATE OF BANK DEGRADATION
θ = CAVING ANGLE OF BANKS
S_N = RATE OF SCOUR NORMAL TO THE STREAM BED
S_X = RATE OF SIDE-SCOUR
S_Y = RATE OF DOWN-SCOUR

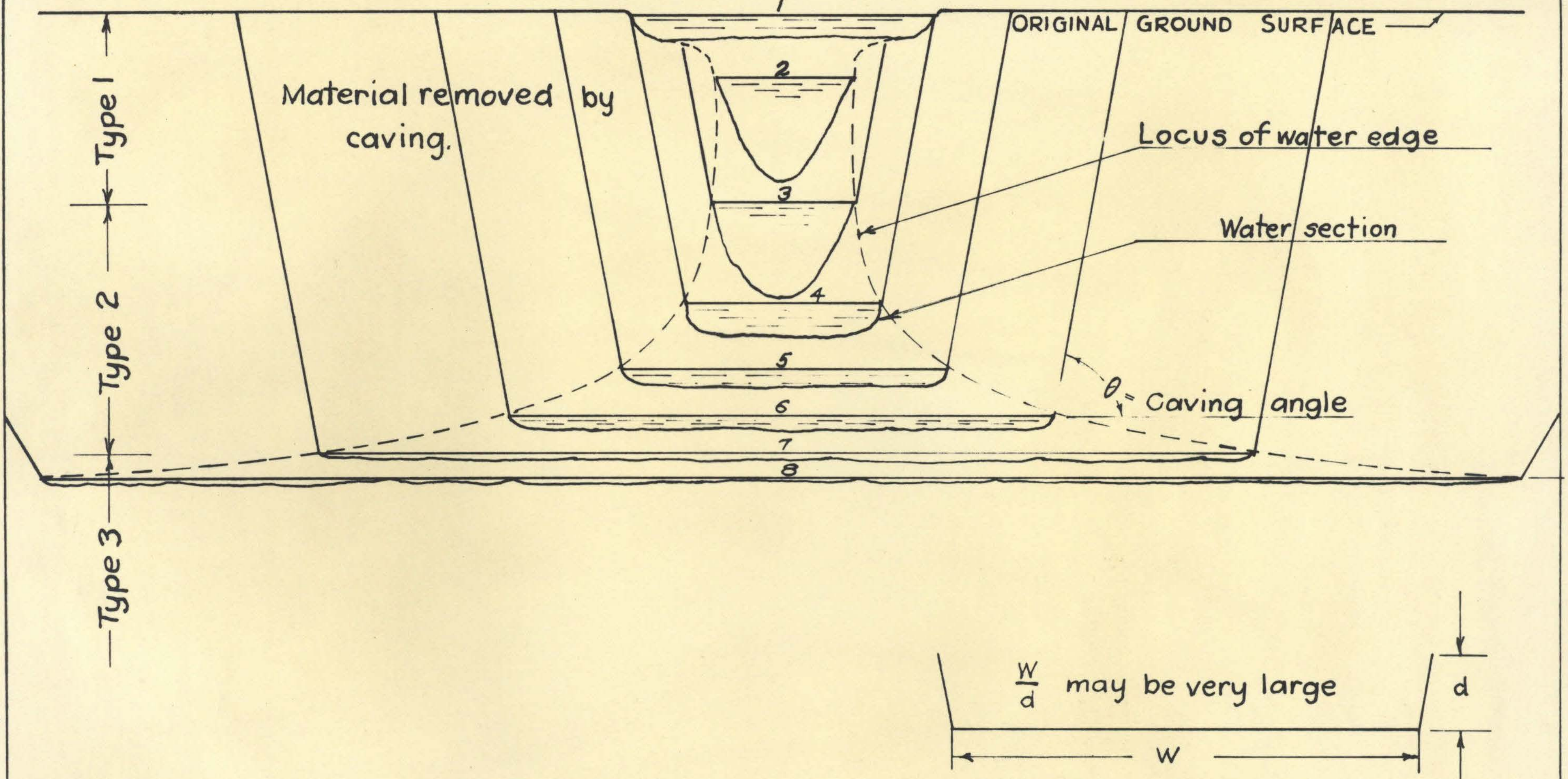
if the number of layers removed by degradation in a given time exceeds the number of layers cut through by the stream. When this is true, the angle of slope is less than the angle of caving and ordinarily there will be no caving due to undermining.

EVOLUTION OF A TYPICAL GULLY

In southern California, water courses which a few decades ago were surface channels, in many cases are now entrenched to depths of 60 feet or more. These gullies are impressive because of their size, their rate of development and the sediment loads in their flows. They are not only impressive! They become alarming when it is understood that many are now in Stage 1 and will, if unchecked, continue their destructive growth until Stage 3 is reached.

Figure 3 illustrates the development of a typical gully cross-section. The stream channel in position 1 represents the pre-gully stage when the water flows in a surface channel. Disturbance of the natural channel bottom or increasing run-off, or both, may start the stream to cut and entrench itself. This first break often changes a wide, slow flowing, non-scouring stream to a narrow, deep and rapidly cutting one. After the first break, the stream soon narrows to a minimum width (Position 2, Figure 3), and cuts rapidly down to Position 3, where side-scour becomes dominant due to the flattening stream grade, increasing silt load, and usually coarsening of the bed material. Meanwhile the average bank slope remains nearly constant as determined by the angle of caving. The stream continues to cut downward and

DIAGRAM SHOWING CHANGES IN GULLY CROSS SECTION DURING DEVELOPMENT



Cross Section of Gully at change from Type 2 to Type 3

FIG. 3

LONGITUDINAL SECTION OF GULLY

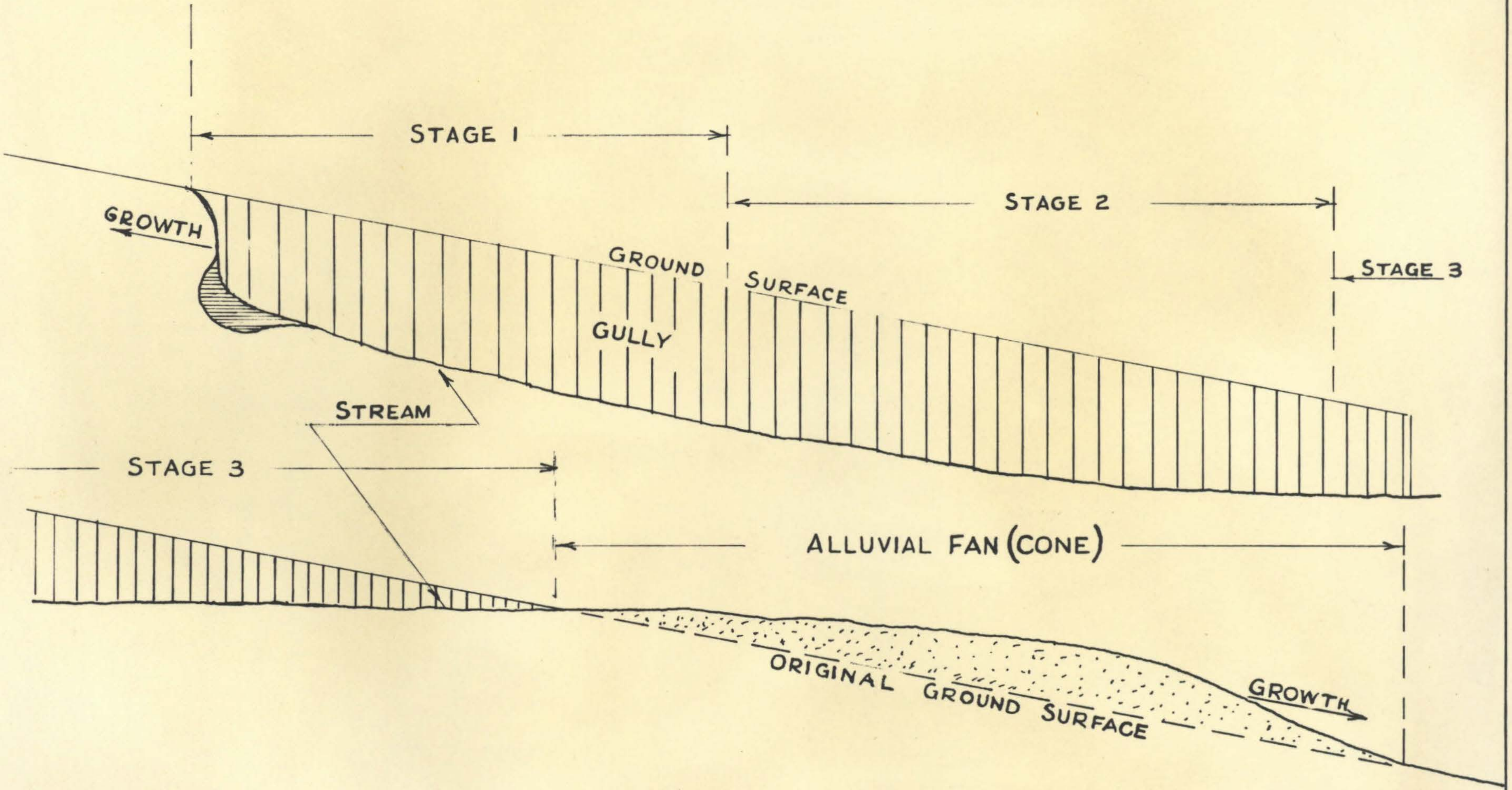


FIG. 4

widen, causing the banks to cave until Position 7 is reached. From this point on, the side slopes flatten because bank degradation is dominant. After caving stops, vegetation is usually able to maintain itself on the sides and, if so, stabilization will result.

While this growth in gully cross-section has been taking place, there has been a corresponding development in the longitudinal section. Figure 4 shows the latter divided into three reaches. In Stage 1, the cross-sections are principally of Type 1; likewise for Stage 2 and Stage 3, the majority of the cross-sections are of Type 2 and Type 3 respectively. There are a number of complicating factors discussed below which will cause overlapping of the stages as well as abnormal cross-sections within them. Furthermore, under special conditions, certain stages may be entirely lacking, but the gully sections illustrated, represent the normal ones to be expected. In this discussion the word "Type" is a descriptive term intended to indicate the geometrical shape regardless of the amount of development which may have taken place. The word "Stage" has been used to indicate how near the gully is to the condition when stability will obtain. Gully reaches of Stage 1, for instance, are far from a state of stability; whereas reaches of Stage 3 are approaching it. The gully represented in Figure 4 had its point of origin near the junction of Stage 3 with the alluvial fan. During its early development it was very much shorter and the part represented in the figure as Stage 3 was then Stage 1. As time passed, the reaches, corresponding to each of the stages, tended to lengthen and migrate upstream. In the reach of Stage 1, the stream gradient was probably quite steep, but flatter downstream in the portions indicated as Stages 2 and 3 in Figure 4. The mouth of the gully may have terminated in another gully, a surface channel, or in an alluvial fan as shown in Figure 4.

FACTORS WHICH COMPLICATE THE CLASSIFICATION OF GULLIES

The more or less idealized gully development discussed above does not consider many complicating factors, the influences of which are minor in comparison to that of the general processes which have been described. Yet they should be enumerated and their effects noted in order that the observer may be able to recognize them and disregard their effects in making a determination of the stage of development at any particular point.

VARIATIONS IN SHAPE OF CAVING BANKS

The caving surfaces of the banks, represented in Figures 1 and 3 as planes, may or not be planes. If the bank is composed of homogeneous material, and has uniform moisture content, these will be surfaces concave toward the gully(R).

Actually, however, such homogeneity seldom occurs in nature, and non-uniform earth masses may often cause rather pronounced irregularities in surfaces resulting from caving, which consequently become widely divergent from those in the idealized cases represented.

[R] Taylor, Donald W.
'Stability of Earth Slopes'
Journal of Boston Society of Civil Engineers,
Vol. XXIV, No. 3, pp. 197 - 246, July 1937.

CONES RESULTING FROM CAVING

The general appearance and shape of a gully of Stage 1 or 2 may be greatly modified by caving banks. Undermining in deep ones may release tons of material at a single time — such quantities, in fact, that the stream sometimes is unable to remove it for several years. These caved portions may form cone-shaped masses in the bottom of the gully and have been observed to become covered with grasses, brush, and even small trees. Cones thus protected by vegetation are comparatively resistant and, as a result, the stream's current is deflected towards the opposite bank where it scours out a horseshoe-shaped cut. Vegetation on such cones does not signify the condition described as Stage 3 under the heading "Evolution of a Typical Gully". In Stage 3 gullies, the vegetation on the banks is the general rule and not the exception, and is found upon undisturbed rather than upon caved material.

CAVING DUE TO MEANDERING

In the previous paragraph, it has been noted that vegetation may exist in gullies of Stage 1 and Stage 2, and it should be pointed out that caving banks may exist in gullies of Stage 3. Consider the case represented by Figure 3, No. 8. When development has reached this stage, there will be a tendency for the stream to meander. At points where currents are incident to the banks, undermining and caving will occur. Deposition at times when the stream is overloaded is one of the important causes of meandering in Stage 3 gullies. This process will be discussed in more detail under the heading "The Effect of Grade Reduction Upon Down and Side-scour".

EFFECT OF SILT CONTENT

The silt content in the stream has an effect in determining whether side-scour or down-scour(R) is dominant. In Stage 2 gullies, if the silt content is suddenly reduced by conservation practices or for any other cause, down-scour may again become dominant, and they will take on the appearance of, or actually revert to Stage 1. On the other hand, a sudden increase in the stream's silt load may convert a gully from Stage 1 to Stage 2. Later on in the discussion of forces acting on soil and rock particles, it will be shown that an increased silt load will reduce the rate of down-scour a greater amount than the rate of side-scour. Thus it may be seen that a variation in silt load complicates classification.

The character of the flow in gullies changes from time to time. Such changes are caused by variations in the amount and distribution of rainfall and by changing land use practices, and are accompanied by corresponding variations in gully cross-sections. Since there are many minor factors influencing development, it may be difficult to find an instance in nature which duplicates the ideal sections illustrated here. In making a classification, therefore, one must think in terms of the average section and disregard the irregularities of any particular one.

[R] National Bureau of Standards Report "Scour of a Sandy River Bed by Clear and Muddy Water" p. 32, November, 1932.

FORCES AND FACTORS WHICH AFFECT DOMINANCE

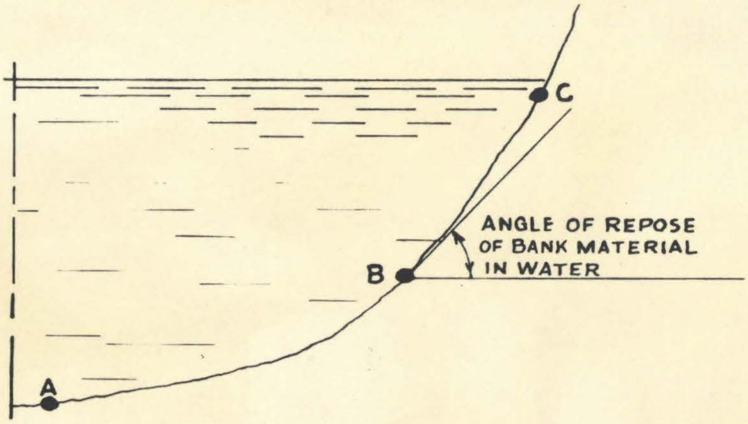
Definitions of what is meant by dominance of down-scour, side-scour, and bank degradation have been given and the general character of the gully cross-sections corresponding to these three cases of dominance have been described. It will be well at this time to investigate the forces and factors determining which of these three processes will be dominant. For this discussion, Figure 5 has been prepared. The right side of a stream cross-section is represented and three particles have been selected for detailed consideration: particle A on a horizontal element of the bed; particle B on an element sloping at the angle of repose of the bank material in water; particle C on an element which has a slope greater than that at particle B. Three force groups act on each of these particles; first, cohesive-adhesive; second, hydraulic; and third, gravity.

COHESIVE-ADHESIVE FORCE GROUP

The cohesive-adhesive group includes all the forces which hold the bank material together. In uncemented sands and gravels this group may be considered equal to zero. However, practically all important gullies are in earth channels, the earth being composed of clay, silt, sand, and gravel in varying amounts. The clay is largely responsible for the tenacity of these materials.

Percentage of moisture has a great effect upon the force of cohesion. Down to the minimum moisture value below which clay crumbles the less the moisture content, the greater is the cohesive force.

FORCES INFLUENCING STREAM SCOUR



FOR CLAYEY CHANNELS

LOCATION	FORCES TENDING TO HOLD PARTICLE IN PLACE	FORCES CAUSING SEDIMENT DEPOSITION	FORCES TENDING TO MOVE PARTICLE FROM BED
A	GRAVITY COHESION	GRAVITY	HYDRAULIC
B	COHESION		HYDRAULIC
C	COHESION		GRAVITY HYDRAULIC

FOR CHANNELS IN LOOSE SAND AND GRAVEL

A	GRAVITY	GRAVITY	HYDRAULIC
B			HYDRAULIC
C			GRAVITY HYDRAULIC

FIG. 5

It has been explained by Terzaghi(R) that the cohesive forces are due to the surface tension in the microscopic films of water which aurround each clay particle. The less the moisture, the tighter these water films become and the greater the forces which hold the clay together. If clay is exposed to water, it gradually expands due to absorption, which begins at the surface layers, slowly penetrates to deeper ones, and thickens the water films surrounding the particles. Thus the cohesive force binding them to the clay mass is reduced. Therefore the clay which is in contact with water, will always have some surface particles having practically no cohesive force to bind them to the clay mass. Such particles may be removed easily by flowing water. It is clear, then, that the rate at which clay may be entrained by a stream will depend upon the rate at which it will absorb water and not on cohesion. For very fine clays this entrainment is often extremely slow.

On the other hand, complete stability of a stream bank will not obtain until the surface particles remain unmoved by the stream. It is evident, therefore, that the cohesion of the clay will have an important effect upon the rate of scour by a stream in a clayey bed, but will not determine the shape of a stable channel. Complete stability is probably never realized, but nature makes an asymptotic approach to this ideal condition.

R
"Compressive Strength of Clay"
Engineering News Record,
pp. 796 - 800, November 12, 1925.

HYDRAULIC FORCE GROUP

The hydraulic force group includes all those resulting from the difference between the velocities of the water and the solid particles. The buoyant force of the water upon particles is, therefore, not included.

The shape of the cross-section has an important effect upon the velocity distribution within the stream, and hence upon the hydraulic force exerted upon the solid particles forming the bottom and sides. An idea of the variation of the tractive force from point to point across the bed may be obtained from the numerous experiments on bed load transport. One of the most widely used expressions for this tractive force is:

$$F = w\ d\ s$$

where F = tractive force per unit area of bed surface, d = depth of flow, s = the slope of the energy gradient of the stream, and w is the unit weight of the fluid.(R)

(R)

1. Hans Kramer,
   "Sand Mixtures and Sand Movements in Fluvial Models."
   A. S. C. E. Proceedings,
   pp. 443 - 483, April 1934.
2. "Studies of River Bed Materials and Their Movement with Special Reference to the Lower Mississippi River."
   Paper No. 17, U. S. Waterways Experiment Station, January 1935.
3. C. H. Mac Dougall,
   "Bed-Sediment Transportation in Open Channels."
   Trans. Am. Geophysical Union
   pp. 491 - 495, 1934.
4. Hunter Rouse,
   "Fluid Mechanics for Hydraulic Engineers."
   Chapter 14.
   This chapter has a complete discussion and bibliography on Sediment Movement.

Some experimenters have developed other expressions for this force which have a somewhat different form. The one here given is in common use and the simplest. It is quite satisfactory for use in this qualitative discussion as a formula which, in general, represents all cases. From it we may draw the conclusions that the unit tractive force along a cross-section varies approximately as the product of the depth and stream slope.

Suppose now that the slope of the stream at a particular section be reduced; the decreased average velocity will cause a corresponding increase in stream section and the water surface consequently must rise. Two opposite tendencies will affect the tractive force on every particle in the bed at this particular section; first, the tendency to diminish it because of the reduced slope, and second, the tendency to increase it due to greater stream depth. But the decrease at the bottom near the center of the stream due to the first tendency will overshadow the slight increase cuased by the second, while near the stream margins the reverse is true. It should also be kept in mind that the decreased slope reduces the total tractive force, and consequently an actual increase in scouring power will be limited to the stream's margins. In other words, a reduced gradient will make down-scour less important and side-scour more so.

GRAVITY FORCE GROUP

The gravity force on the particles is equal to the effective attraction between them and the earth. This will be equal to the weight of the particles minus the weight of the water displaced. This force will act on all particles whether they are in the bed, moving as bed load, or as suspended load.

The effect of gravity upon any one particle in the bed will depend upon its location. The gravity force exerts its greatest stabilizing effect upon horizontal elements (Figure 5 Particle A) which will usually be near the center of the stream. As we proceed from the center towards the edge along a cross-section, the elements of the bed will ordinarily have greater and greater slopes, and consequently the component of gravity effective in holding the particle in place will become less and less. If this slope equals the angle of repose of the material in water (Figure 5, Particle B), the effect of gravity will be nil. If the slope is greater than at Particle B (Figure 5), the forces of gravity will tend to tear the material away from the bank (Figure 5, Particle C). If there is no cohesive-adhesive force present, slopes greater than the angle of repose are impossible. Such slopes can only occur when the bank material is held together by cohesion, adhesion, or such forces as may be exerted by plant roots.

When a stream is carrying material, the force of gravity will tend to deposit it while hydraulic forces will cause bed material to be entrained and there will be an exchange between the stream and the bed. If the rate of deposit exceeds that at which material is being picked up, the stream becomes a depositing one, the channel becomes shallower and the flow is forced out toward the banks causing excessive side-scour and, if the depositing is heavy, the entire channel may become filled, cuasing the stream to abandon its former course. When banks are steeper than the angle of repose of material in water, side-scour occurs not only because the channel is filling, but also because on such slopes there can be no exchange of material. It is hardly to be expected that material torn away from such banks can be replaced by deposits from the stream, as is the case along the bottom of the channel.

In a given flow both the gravity force and the hydraulic force increase with an increase in particle size. The ratio,

$$\frac{\text{gravity force component effective in holding particle}}{\text{hydraulic force component effective in moving particle}}$$

, may be considered as a sort of stability index. Particles in the bed are completely stable when this ratio is greater than 1 and the particle moves when the ratio is less than 1.

By observing their rate of fall in water, an idea may be obtained of the velocities of flow required to move particles of various sizes. Since large particles fall more rapidly through water than small ones, they can withstand higher velocities of flow, and it follows that, for a given flow, the stable grade is steeper for coarse than for fine material. The excellent body of research on the force exerted on spheres by moving fluids gives only a partial basis for estimates of the value of this ratio. But future extensions of fundamental knowledge will no doubt make this basis complete.(R)

R

1. Hunter Rouse,
   "Nomogram for the Settling Velocity of Spheres"
   National Research Council, Division of Geology and Geography,
   Washington, D. C.
   Exhibit D of the Report of the Committee on Sedimentation,
   1936-37, pp. 57 - 64, October, 1937.
2. For further references see bibliography given in this article.

THE EFFECT OF GRADE REDUCTION UPON DOWN AND SIDE-SCOUR

By using the concept of the particles lying in a stream channel being in equilibrium under the action of the three force groups just described, it is possible to diduce what effects certain changes in the channel will have upon down-scour and side-scour. Let us consider, for instance, what will be the result of artificially reducing the gradient in a gully by means of a soil-saving dam.

The velocity of flow will be decreased and if the discharge is the same, the a area of the stream cross-section must increase and the surface of the water will be raised by a corresponding amount. These changes will cause a re-distribution of the hydraulic forces from point to point across the stream bed. As already described under the discussion headed "Hydraulic Force Group", there will be a reduction in the hydraulic forces acting on particles forming the bed near the center. At the very edge of the stream, on the other hand, there will be an increase in the hydraulic forces acting on bed particles. This increase is apt to be confined to the regions close to the edges, and the overall effect will be a reduction in carrying capacity which, if the stream already has a capacity load, will cause deposits near its center.

The total gravity force on each of the particles will be unchanged by the artificial reduction of stream gradient, but the component of gravity, which is effective in holding the particles in place, will depend upon the slope of the bed. Near the center of the stream the effective component of gravity will be increased because of slope reduction due to silting. The extra side-scour induced by the increase of hydraulic forces near the edges, and the stream currents which are forced toward the edge by center deposits will almost invariably cause an increase in the bank slope near the margins of the stream. In turn, this increase in the slope of the bank will decrease the component of gravity which is tending to hold the bank particles in place. It is clear, therefore, that a reduction in grade so alters both the hydraulic and gravity forces as to reduce down-scour and increase side-scour.

Side-scour is seldom uniform along a channel. The tendency is to gouge out the softer spots, forming concave cuts in the banks. As the current leaves these cuts, it is deflected across the channel and impinges upon the opposite bank some distance downstream forming a cut of similar shape, and then continues to zigzag causing heavy scour at every point where the current is incident to the channel bank. The curvature of these cuts has a tendency to become sharper and sharper as this localized side-scour proceeds, and the rate of side-cutting is accelerated, in turn, by the increase in curvature. There is a further tendency for all these horseshoe-shaped cuts to migrate downstream. By the process here described, it is possible for a stream during a single flood to increase its width greatly. Also by this process streams are able, during flood periods, to cut around the ends of bridges, dams, or other structures which may span them.

EFFECT OF STREAM SORTING UPON DOWN AND SIDE-SCOUR

Another factor, which may have an important bearing in determining dominance, is sorting by the stream. Stream sorting will cause the bottom of a channel to be lined with the coarser particles derived from its banks. The larger these particles become in relation to adjacent bank material, the greater will be the tendency of the stream to side-cut and abandon its channel.

The effects of sorting depend upon the character of the channel. In a rock canyon, for instance, they are very unimportant because there is solid rock below the gravel and sand bed as well as on the sides of the stream. During major floods, the gravel and sand may be almost entirely removed, but the limiting boundaries of the channel are determined by the rock gorge. A gully channel in earth, on the other hand, has no hard boundary to limit ultimate scour. If the stream abandons a bed which has become resistant because of residual particles left by sorting, it will tend to remain out of it. The long time tendency then will be always to force the stream to cut sideways and abandon its channel, and by this process it may be forced to sweep back and forth across the plane traversed.

THE EFFECT OF SEDIMENT LOAD UPON THE DETERMINATION OF DOMINANCE

The presence of sediment in a stream probably has two effects which are important to the problem of gully control. First, the stable grade for a stream is made steeper by sediment in the flow and second, side-scour becomes more important relative to down-scour. These effects together will shift upstream the point of transition from Stage 1 to Stage 2 (See Page 12).

In order to develop the argument supporting these conclusions, consider the balance which exists between a loaded stream and its bed. If the stream is scouring, it is taking material from the bed faster than it is supplying material to it. On the other hand, if the stream is depositing, the rate of supply to the bed exceeds the rate of entrainment. It is balanced if the two are equal. If extra load is added to such a stream, deposition at certain points must occur causing a steepened grade which supplies the extra scouring force necessary to bring it again into balance. The assumption which has been made here, that the absolute rate at which particles pass from the stream to the bed increases with the number of particles in suspension, and that there is not a proportionate increase in the rate of entrainment, is reasonable for all normal flows. If the concentration becomes high, both the density and viscosity of the flow increase and the above assumption becomes questionable. However, actual observations of mud flows seem to indicate that a relatively steep grade is one of the conditions necessary for their occurrence. Therefore, for this qualitative discussion it is probably safe to conclude that the stable slope gets steeper as the load of the stream increases.(R)

R
E. W. Lane,
"Retrogression of Levels in Riverbeds Below Dams"
Engineering News-Record,
Vol. 112, pp. 836 - 838, 1934.

Consider now the argument to support the conclusion that sediment load causes side-scour to become more important relative to down-scour. The argument rests upon the differential effect which the force of gravity has upon particles in the bottom of the bed and upon those in the bank. Suppose there is an increase in the amount of sediment being transported. Extra particles will be deposited on the bed at all points across the stream section. The number of these particles which will remain on the bed will depend upon the component of gravity effective in holding the particles. The magnitude of this gravity component is a maximum for the horizontal elements near the center and decreases toward the stream margins where the slope of the bed is greatest. More particles will therefore be deposited and retained at the center than at the sides. As a result, down-scour will be decreased and side-scour becomes relatively more important. This will be true whether down-scouring or side-scouring is dominant. An addition of silt load, therefore, will force a stream to widen whether it is scouring or depositing. This is one reason why excessive side-scour may sometimes be observed in sections where deposits are accumulating upon the bottom. It is not the intention of this discussion to include mud flows. In them the great changes in density and viscosity are additional factors which would have to be considered.

TWO POINTS OF VIEW IN MAKING EVALUATIONS OF GULLY CONTROL STRUCTURES

In attempting to evaluate the effectiveness of structures intended for gully control, either a short or a long time point of view may be adopted. The first does not take into consideration the eventual changes which may be expected within a gully. It attempts only to determine whether or not the control structure is the most economic one which will safely pass the expected floods, assuming that the character of the gully remains the same as at the time of construction. Such an evaluation may be made by model studies or by observing the actual structures during a maximum flood flow.

Dams pronounced adequate from a short time point of view may fail ultimately due to changes which are constantly occurring in the channel. Because of this fact, the long time point of view attempts to visualize the nature of the channel when complete stability has been reached, and on the basis of this picture appraise structures to see whether they will remain adequate until stability is accomplished.

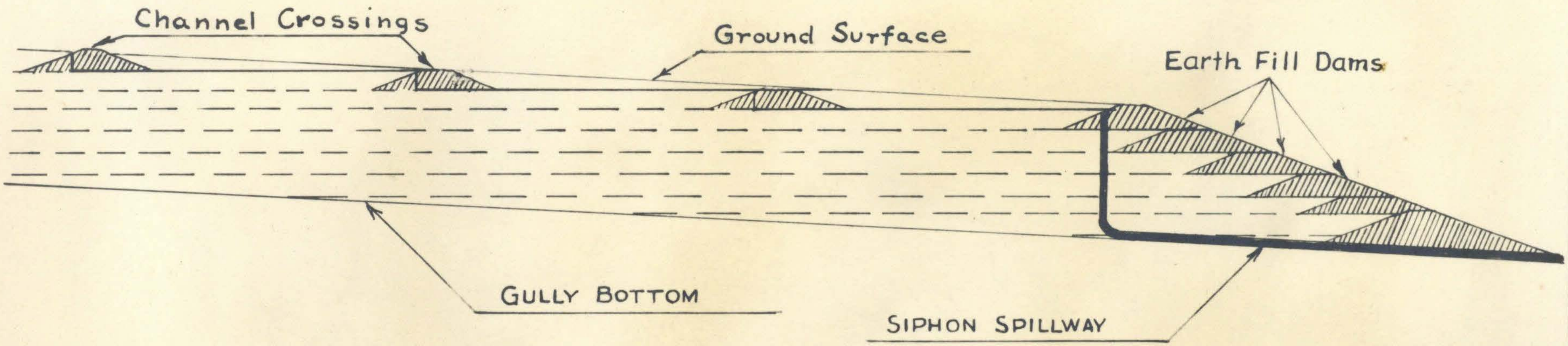
RESPONSE OF GULLIES TO VARIOUS TREATMENTS

The general principles of gully development, which have been described, may now be used to predict the response which a given one will make to a particular type of treatment. For example, a common procedure for those of Type 1 is to construct a series of check dams which stops deepening and longitudinal development. This treatment has been widely used. The method is about as follows: By field observations a maximum non-scouring gradient is selected. Dams are then built so that the fall from the toe of one to the crest of the next is as much as the selected gradient will allow. The slope of a stabilized bank is then chosen and the length of the wing walls designed accordingly.

The dangerous assumption, which has been made, is that the stream will not widen. If the foregoing analysis of the processes and forces causing erosion is correct, we should expect this treatment to change a gully of Stage 1 to Stage 2. In other words, side-scour will become dominant and the channel will widen. Shortly revetment protection will be necessary to prevent the flow from going around wing walls since the weak points are the channel sides immediately adjacent to the structures. Additional side protection will probably be necessary within a few years after construction. Such repairs do not eliminate weak points. They merely shift them to new locations and subsequently other repairs will be needed repeatedly until, in effect, there is a lined channel between the original structures. Only then is complete control of the stream obtained.

At this point mention should be made of a second method of protecting the original structures; i. e. adding soil-saving dams between them. This treatment will reduce the stream to a series of ponds in which velocities are lowered, thus causing the channel to be partially filled with silt and, normally, causing the bed to become wider. The advantages of this method over the one already discussed is that cushion pools of adequate depth may be created and the velocity of flow controlled along the entire channel by these closely spaced structures. If this method is properly combined with shaping and planting of the banks, it should give complete protection, although it may be somewhat expensive.

Protection of the channel by use of vegetation between the original structures has been suggested. For gullies of minor size or of Stage 3, this may serve very well, but for those of major proportions with caving banks, its effectiveness is questionable. In order to hold the gully where it is, both down-scour and side-scour must be stopped. For major ones of Types 1 and 2, this would frequently require a ditch lined to withstand high velocity flows. Even if such a ditch is constructed, the gully may be expected to widen at the top due to bank degradation.



METHOD FOR RECLAMATION OF LARGE GULLIES OF TYPE 1 & 2

FIG. 6

SUGGESTED METHOD OF CONTROL FOR MAJOR GULLIES

The formulation of a set of rules for gully control will not be attempted in this paper. A few suggestions will be made, however, which are considered pertinent to control when, as in southern California, gullies traverse land of high value.

Reaches in Stage 1 may be expected to cause the greatest future damage if allowed to continue without complete or ultimate control. In the light of the principles set forth in this paper, it would seem unwise to attempt to stop the development where it is and hold it there. The two remaining alternatives are; first, let the gully develop; second, reclaim it. Upon first consideration reclamation may seem too costly, but where land value is high a more careful analysis will probably show that reclamation will be by far the most economical procedure as a long-time policy.

In order to illustrate a possible method for accomplishing this, consider a gully about 6,000 feet in length with a maximum depth of 30 feet. Near its head are cross-sections of Type 1 for approximately 2,000 feet; in the central portion a similar length in which Type 2 predominates, and finally a sub-equal section of Type 3. Somewhere near the upper end of this third reach a point is chosen, marking the downstream end of the portion to be reclaimed. Below this point control will be effected by means of vegetation without structures. Above it an attempt will be made to reclaim the gully and restore the flow to a surface channel.

The first act would be to construct at this selected point a dam of sufficient height to raise the water surface in the resulting reservoir approximately to the top of the gully banks. When the reservoir silts up to the crest of the spillway of this dam, a second structure will be built at such distance upstream that the drop through it will be about 4 feet. This will create a second reservoir which, being shallow, quite possibly will silt up in a single wet season. During the next dry period a third dam, similar to the second, will be located an appropriate distance upstream creating another shallow reservoir which should silt up in a reasonably short time. In this manner, step by step, treatment may be continued upstream throughout the entire gully leaving behind a series of rather closely spaced, low, inexpensive dams. It is necessary that the potential supply of silt be ample to fill the gully ultimately. Such rapid silting as has been widely observed in southern California, indicates that in this region, at least, the supply is ample.

The surface channel resulting from this method of treatment will ordinarily be wide when compared with the flow channel before reclamation was initiated. In some cases, this width will be excessive, making it possible to restore a portion of the reclaimed area to farm use. A channel of ample width must always be maintained to take care of run-off, and may take the form of a meadow-strip waterway with banks shaped to permit farm equipment to cross. In most cases proper vegetation can and should be established in the surface channel to resist the erosive action of subsequent flows. The dam crests may be constructed to give a series of convenient crossings where farm machinery may be moved from one side of the water course to the other without damaging the channel.

It now becomes desirable to consider more in detail the construction of the first dam. Figure 6 has been prepared in order to illustrate a method which is deemed feasible and economical. First, build an earth dam of suitable height and shape so as to bring the water surface in the channel to be reclaimed to the elevation desired. Install a siphon spillway and build the riser just high enough to avoid excessive pressures and deposit a sediment layer of desirable thickness, i.e. 2 to 5 feet, during the first season of run-off. (Silt estimates may be based upon field observations.) At the downstream end of the sloping discharge pipe erect an earth embankment sufficiently high to avoid danger of overtopping. Silt subsequently deposited will now raise the floor of the gully to a point even with the top of the spillway riser. Dry periods following silt deposition will cause compaction due to evaporation from the surface.(R) Later, as in the first case, teams and machinery may be used in constructing a second earth embankment to be laid on top of the old one as Figure 6 shows. The height of the riser may now be increased and it is ready for another season's run-off. In this way, step by step, one may create a dam of the desired height. When it is finished and the reservoir filled, the deposited silt will extend a considerable distance upstream.

During the next dry season a second dam of small height should be erected upon the silt bed which has been deposited by the first dam.

R
Charles Terzaghi,
"Phenomena of Cohesion of Clay"
Engineering News-Record,
pp. 742 - 746, November 5, 1925.

After the small shallow reservoir created by this new structure has been silted up, a third dam may be located upstream. By this method as can be seen in Figure 6, the actual amount of fill which must be placed by mechanical means is relatively small since filling by the stream itself is utilized. The expense of this type of treatment is proportionately small. In most cases, standard reinforced concrete pipe may be used for the spillways. Immediately upstream, earth for the small embankments may be obtained from the sides and bottom of the gully itself.

There are several factors which tend to make this method of treatment safe; first, because each dam in the series is low, at no time will the hydrostatic pressures be very great, as would be the case if a single large dam was constructed; second, the lapse of time and the drying process, which will often take place after deposition of a layer of silt, will cause it to be compacted; third, in many cases finer and less permeable materials will be deposited near the dam, thus tending to reduce the amount of seepage; fourth, greater protection against surface wash is provided on the downstream slopes of previous fills because vegetation has had time to become well established.

In some cases where the soils are largely composed of clay, cracks in the silt bed may develop during the drying season. If this happens, some provision should be made for compacting the silt layer near the dam at the time the earth embankment and spillway inlet are raised.

To work successively from the downstream point toward the head of the gully may require too long a period. If this is true, reclamation may be started at several points with properly designed dams and spillways. If, however, the total amount of silt which is retained is not increased, the time required for reclamation will be the same. The rate of filling depends upon the amount of silt carried by the stream. It may be desirable to adopt the second policy in order to reduce the thickness of the silt layer and thus obtain better compaction. Provision should be made to stop headward erosion of the gully during the reclamation period.

There is some objection to the use of siphon spillways on the ground that there is danger of clogging. If this be the case, all the dams after the first may be provided with chute-drop or other type spillways. The siphon spillway, however, lends itself very nicely to the method described for constructing the composite dam (Figure 6). If a spillway of the chute-drop type is wanted for this dam, it will have to be added after completion. Of course a dam of the size needed for complete reclamation may be constructed at the outset and provided with such a spillway, but it should be possible to protect the siphon type sufficiently against clogging so that it may be used and the benefit of the additional economy obtained. For complete reclamation, the potential supply of silt must equal the volume of the gully reclaimed. It is felt that this supply usually will be adequate, and in most cases far in excess of the amount needed. If heavy silt flows still continue after the gully has filled, additional precautions must be taken to prevent the stream from silting up its restored channel and scouring a new one in some other location.

Economic reasons will ordinarily demand a spillway insufficient to pass unusual peak run-offs. To provide for these an auxiliary spillway may be used to by-pass the excess amount of flow around the dam and into the channel a safe distance downstream.

Temporary storage during times of peak run-off may also be desirable as a means to reduce the size of spillways for the soil-saving dams. Small detention reservoirs may be created by extending crests of dams a few feet above the gully banks, and continuing them along the contours of the surrounding country. Storage thus created may substantially reduce peak flows because the drainage areas are frequently small and the duration of the peak run-off short.

Before these suggestions can be of wide use in gully control, modifications arising from field conditions will probably be necessary. The essential point to be kept in mind is that the method of treatment should be based upon an understanding of the principles of gully development. Attention is called to the fact that the treatment which has been suggested is for a special case and is not universally applicable. It was assumed that the lower end of the gully was in Stage 3 and that the potential silt load was sufficient. It was further assumed that land values were high enough to make reclamation economically feasible. Discussions of many other cases of gullies in various stages of development or in other parts of the country have been reserved for future papers.

PLATE I

A Stage 1 Gully

The Milligan Barranca near Santa Paula, California, is a major gully, and at the point illustrated is in Stage 1 of its development. Note the V-shape cross-section and caving banks.

PLATE 2

CALIF-RI

A Stage 2 Gully

Note the truncated V-shape and caving banks of the Milligan Barranca in this illustration. A soil-saving dam some distance downstream from this point has caused the gully to silt up to a depth of about 20 feet. This treatment has changed the gully in this reach from Stage 1 to an artificial Stage 2. For a time accelerated side-scour will continue, but as the channel widens, the rate of side-scour will be so reduced that bank degradation will become dominant and ultimate stabilization result.

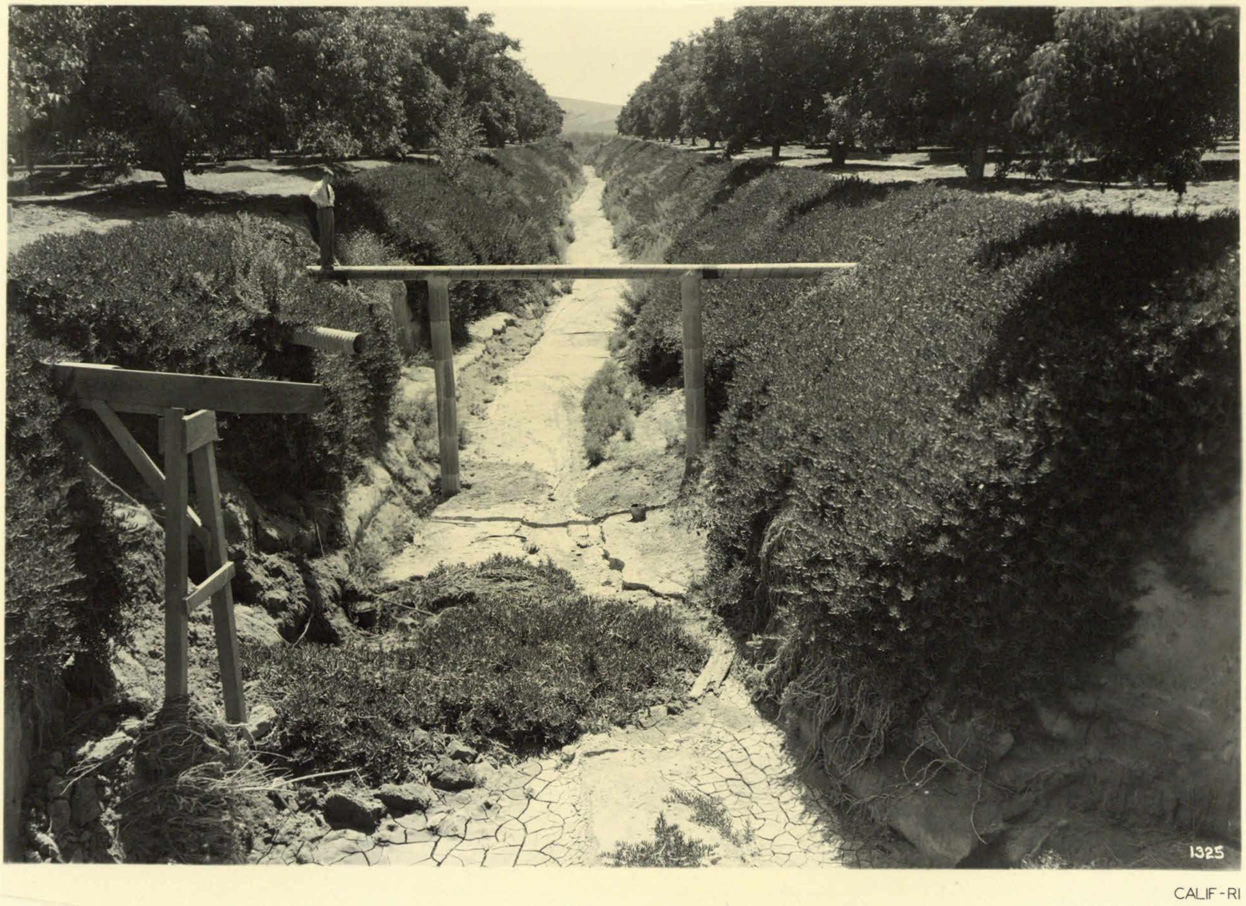
PLATE 3

CALIF-RI

A Stage 3 Gully

The Los Posas Barranca near Santa Paula, California. Note the V-shape and banks covered with vegetation. A natural obstruction due to a land slide located a short distance downstream from this point has been recently cut through by the stream, and the gully is reverting to a Stage 1 gully. Caving banks may be seen in the lower left hand corner of the picture.

PLATE 4



A Stage 2 Gully With Artificially Sloped Banks
Which Have Been Planted

The banks of this Stage 2 gully were sloped and planted, but the width of the flow section was not sufficient. Although side-scour was reduced by the vegetation, it still remained dominant, and the gully section is reverting to Type 2. The patches of lighter colored vegetation are regions of old slips similar to the one in the foreground. The stream grade is stabilized by a soil-saving dam.

PLATE 5

A Stage 1 Gully After Partial Reclamation

Silting, resulting from a soil-saving dam, has practically reclaimed this gully. The brush covered silt deposits in the gully indicate that in this case a stable channel can be established within the old banks if the entrenched channel is raised to the surface by silting.