Paper No. 68-749

RELATION BETWEEN LAND-SLOPE SHAPE AND SOIL EROSION

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Abstract

The effect of initial slope shape on sediment load and depth of erosion, and the change in slope shape as erosion progresses were analyzed for different land-surface profiles. Erosion and sediment losses were greatly reduced by concave shapes.

For presentation at the 1968 Winter Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Sherman House

Chicago, Illinois

December 10-13, 1968

1-19-60

RELATION BETWEEN LAND-SLOPE SHAPE AND SOIL EROSION[1]

L. D. Meyer and L. A. Kramer[2]

The topography of sloping land includes countless natural forms, and man often shapes such land into other forms. The shape of a hillside may greatly affect the intensity of erosion at different locations along the slope. Conversely, different erosion intensities along a slope may appreciably change the slope shape as erosion progresses. The purpose of this research was to study the land surface shapes that would result from progressive erosion of selected initial slope shapes as predicted by different erosion equations. Eroded depth and sediment load at any location along the slope were also computed. Knowledge derived from this approach may be used to predict locations of critical erosion on slopes and rates of sediment movement from slopes as well as slope shape changes. Such information is applicable both to farm fields and construction sites.

Background

Various equations have been proposed to describe quantitatively soil erosion as a function of slope steepness, S, and slope length, L. Zingg (9)

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[1] Contribution from the Corn Belt Branch, Soil and Water Conservation Research Division, Agricultural Research Service, USDA, in cooperation with Purdue Agricultural Experiment Station, Purdue Journal Series Paper No. 3529.

[2] Agricultural Engineers, SWC-ARS-USDA, Lafayette, Indiana and Columbia, Missouri, respectively.

proposed the form, total erosion for a unit width of slope = $C_z S^{1.4} L^{1.6}$, to describe soil loss by water. Smith and Wischmeier (6) proposed the relationship, erosion per unit of area = $C_{sw}(0.43 + 0.30\ S + 0.043\ S^2)\ L^{0.5}$, or total erosion = $C_{sw}(0.43 + 0.30\ S + 0.043\ S^2)\ L^{1.5}$ to represent the soil erosion process. Horton (1) derived an equation where total erosion = $C_H\ f(S)\ L(L^{0.6} - L_c^{0.6})$. Meyer and Monke (3) suggested the form, total erosion = $C_L(L - L_c)^n$ for a given steepness, or total erosion = $C_s\ (S - S_c)^m$ for a given length, where L_c and S_c are critical values. These were subsequently combined as total erosion = $C_M\ L^n\ (S - S_c)^m$, where the critical steepness at which appreciable erosion begins, $S_c = K/L^u$, and K is a constant (2). Each subscripted C above includes other variables that were assumed constant for this study. All foregoing relationships except Horton's were obtained by empirical analyses of available data from rectangular runoff plots of various lengths and steepnesses. Each plot, however, was of relatively uniform slope.

Young and Mutchler (8) measured erosion from three slope shapes: concave, convex, and uniform, using the best available sites that could be located on natural land slopes. Subsequent studies by Young and others (7) have been conducted on areas that were mechanically shaped to obtain more characteristic forms of these shapes. This research showed that slope shape is a major factor in soil erosion and that the steepness of the bottom portion of a slope is a major factor in determining the relative erosion. Onstad et. al. (5) studied the same three shapes in relation to erosion from natural field slopes. They concluded that use of specific slope steepnesses as they vary on a slope was an improvement over an estimate of soil erosion based on mean slope steepness.

Procedure

Four slope shapes, identified as uniform, concave, convex, and complex (upper half convex, lower half concave), were studied during this investigation at two mean slope steepnesses, 5% and 10%. All initial shapes had a 20-foot elevation difference between the top and bottom of their sloping portions (see Figure 1). These conditions were of particular interest, but the procedure is applicable to other conditions as well. A numerical approach to solving the erosion prediction equations was found to have major advantages over the analytical approach, and it was used throughout this study.

Three forms of the total erosion equation were studied. The Zingg form was used as: Sediment load = $5.0 \times 10^{-6} S^{1.4} L^{1.5}$. The Smith-Wischmeier form was used as: Sediment load = $1.585 \times 10^{-5} (0.43 + 0.30 S + 0.043 S^2) L^{1.5}$. To study the effect of including critical limits below which appreciable erosion does not occur, the form: Sediment load = $1.32 \times 10^{-5} L^{1.5}(S - S_c)^{1.4}$, where $S_c = 50/L^{0.5}$, was also studied. The constant and exponent in the last relationship were averages found from laboratory studies on fine sand (2). For all expressions, S is in percent and L is in feet.

The coefficient in each of these three equation forms was selected such that one erosion period (defined as one iterative solution of the total erosion equation) produced about 40 tons per acre from a 5% slope

400 feet long. This is the average annual soil loss on a Bedford silt loam soil in southern Indiana cropped to continuous corn.

A digital computer program was developed to compute the total erosion load at the end of each 10-foot increment of slope based on the steepness at and the length from the top of slope to that point. The net erosion or deposition between the ends of adjacent increments was the difference in the sediment load at these points. Similarly, the depth of erosion (assuming a soil bulk density of 100 pounds per cubic foot) at each location was determined as the sum of the net erosion for the two adjacent increments divided by the length of these two increments. New elevations and steepnesses were computed at each point for each successive period of erosion. This iterative process was repeated for a given number of erosion periods. The computer program also produced the input data for a Calcomp plotter used to plot the resulting slope profiles and sediment loads as shown in the accompanying figures.

This approach required the assumptions that the soil was uniform and that sediment load at any location could be obtained from the slope steepness at that location and the length to the location from the top of slope. Although these assumptions are questionable, except for noncohesive, uniform-sized soil, they are sufficiently useful for studying general trends concerning how slope shape is affected by progressive erosion and, conversely, how erosion is affected by slope shape. For a more descriptive approach to the erosion process, the reader is referred to another paper (4), but the more complicated analysis there was not warranted for the current stage of this investigation.

Data

A sample of the numerical output from the computer program is given in Table 1 for the complex slope shapes averaging 5% steepness during erosion periods 1, 51 and 201. This example is based on Zingg's equation with the slope divided into 10-foot increments.

Some of the results from this study are illustrated in Figures 1 through 11. Results are reported only for conditions with a flat area, such as a lake or marsh, beyond the toe of the slopes. Other end conditions were studied, but the development of the slope shapes was not greatly affected whether the portion beyond the toe was flat or slightly sloping, or whether it terminated with an overfall that prevented downcutting. For the flat area, deposition occurred at the toe of the slope and extended out onto the flat area as erosion progressed. Thus, the elevation at the toe often increased several feet and this influenced the profile near the bottom of the slopes.

In Figure 1, profiles of the initial slope shapes are shown with the vertical scale expanded ten times the horizontal. The profiles for these shapes after 50 periods of erosion are shown in Figure 2 for Zingg's equation. The profiles after 200 periods of erosion are shown in Figure 3. The Zingg profiles after 50 periods of erosion are compared with profiles of the Smith-Wischmeier equation in Figure 4. The original and fiftieth period profiles using Zingg's equation are compared with the Period 50 profiles predicted when using critical values in Figures 5 to 8.

The preceding figures illustrate how progressive erosion changes the profiles of different-shaped slopes. These profiles develop differently because the depth of erosion varies for each slope shape. The intensity of erosion along the slopes and the total sediment load at the base of the slopes are indicated by Figure 9 for the first period of erosion on the various slopes. The curves show the total erosion or sediment load along the slope. The relative net depth of erosion is indicated by the difference between the load at successive locations. Where the slope of the sediment load curve is positive, erosion is occurring; where the slope is negative, deposition is occurring. The sediment loads predicted during the initial erosion period by the Zingg and Smith-Wischmeier equations are compared for several conditions in Figure 10. The sediment loads for these same shapes after 50 periods of erosion as predicted by the Zingg equation are shown in Figure 11.

Discussion

Although the main variable of interest was slope shape, the effects of several other variables--slope steepness, type of erosion equation, and inclusion of critical values in the erosion equations--were also studied to a limited extent. Each of these is discussed in the following sections.

Effect of slope shape. Fifty periods of erosion changed the profile of the convex shape the most and the concave shape the least (Figures 2, 4, 5, 6, 7, and 8). The uniform slope developed a concave profile, and the initially complex slope also developed a concave profile except at the very upper part of the slope. After 200 periods of erosion, all slope shapes tended strongly toward concave profiles as shown in Figure 3. The reasons why some slope shapes changed more rapidly than others may be seen from the sediment loads along the various-shaped slopes during the initial period of erosion in Figure 9. Although the sediment load was low at the upper portion of the convex slope, where the steepness was quite small, it increased very rapidly as slope steepness and slope length (quantity of runoff) increased toward the end of the slope. In contrast, the concave slope had the greatest steepness where the least runoff occurred, at the upper portion of the slope. The steepness then decreased as the runoff increased so that the total sediment load at any point was relatively low, and the total sediment movement on the slope (indicated by the area beneath the curves) was much lower for the concave than for the convex slope. Thus, the concave shape was not changed as rapidly as the convex.

The sediment load of the uniform slope increased steadily as length increased, to a value higher than the maximum for the concave slope but much less than for the convex slope. For the complex slope, the sediment load reached a maximum nearly equal to the maximum of the uniform shape about two-thirds the way downslope, where the slope was still steep and the runoff was large, but then decreased as the slope steepness decreased even though the length increased. During the first period of erosion, maximum sediment loads for the 5% slopes varied from 0.14 units about halfway down the concave slope, to 0.32 units about two-thirds of the way down the complex slope, to 0.37 units at the toe of the uniform slope, to 0.92 units at the toe of the convex slope. Note that the maximum loads for these shapes on a 10% slope were slightly less (0.13, 0.30, 0.33, and 0.80 units, respectively). After 50 periods of erosion, the maximum rates decreased because of slope shape changes during the intervening time, as shown in Figure 11. Thus, the intensity of erosion tends to diminish with time if all other conditions remain the same.

Where sediment is a problem, the load predicted off the ends of the different slope shapes is of particular interest. For the concave and complex slopes, most of the sediment carried from the upper portion of the slopes was deposited in the lower one-third of the slope length, and a relatively small portion was indicated as being eroded from the base of the slope onto the area beyond. In contrast, however, the uniform and convex slopes were carrying large quantities of sediment at their bases. Since sediment is being recognized more and more as a serious consequence of soil erosion, the shaping of at least the lower portions of long slopes to a concave shape is indicated as an important step toward reducing sediment movement from a slope.

The depth of erosion along the different slope shapes may also be of interest. The maximum depth (based on uniform removal) during the first erosion period for the 5% slope ranged from 0.019 foot near the top of the concave slope to 0.028 foot at the end of the uniform slope to 0.044 foot just above midway for the complex slope to 0.129 foot at the end of the convex slope. At 10%, the depths were greater (0.035, 0.051, 0.080, and 0.218 foot, respectively), but in the same rank.

Effect of slope steepness. The major effect of different steepness of slope indicated from these analyses is that steeper slopes change shape more rapidly because of their greater depth of erosion per unit of time. Data in the previous paragraph shows that the 10% slope shape changed about twice as fast as the 5% slope.

Comparison of the sediment loads indicated for the 5% and 10% steepnesses at corresponding elevations shows very little difference in their magnitudes. The increased steepness of the 10% slope was approximately compensated by the decreased length and consequent reduced runoff. Although net losses at any slope length were greater for 10% because the sediment load curves were steeper, the total sediment loads from the ends of the slopes and at any elevation downslope were very similar for the 5% and 10% steepnesses. This analysis indicates that sediment losses from a slope of given shape will be similar at the toe whether a steep slope or a longer, less steep slope is used for a given change in elevation. Thus, the use of a moderately steep slope with a flattened portion beyond the toe for sediment deposition may be preferable to a less steep, longer slope with no flattened portion at the end.

Effect of erosion equation. The slope shapes predicted by the Zingg equation and the shapes predicted by the Smith-Wischmeier equation are very similar along the initially sloping portion as shown in Figure 4. However, near the toe of the slope and beyond, the curves indicate slight differences. The Zingg equation predicted all sediment to be deposited near the toe of the slope, whereas the Smith-Wischmeier equation predicted some erosion beyond the toe of the slope as shown in Figure 10. However, effect on general slope shape was small, and this analysis indicated that the predicted shape of these slopes, for the steepnesses studied, will not greatly depend on the type of equation used.

Effect of critical values. The effect of including critical steepness in the Zingg-type erosion equation is indicated in Figure 5 through 8 after 50 periods of erosion. Erosion at the top of the slope was less (zero for the first sections) and the movement of soil ceased sooner at the toe of the slope when critical limits were included. The land slope profiles predicted by erosion relationships that included critical values resemble field slopes more closely than do those predicted by equations without critical values. Equations with critical values predict the "belt of no erosion" near the top of slope, discussed by Horton (1).

When critical values were included, all original shapes except the concave soon developed complex profiles having inflection points somewhere along the upper half of the slope. Field slopes commonly develop similar shapes. As erosion progressed further, these complex shapes became dominantly concave.

Application of results. Information concerning erosion rates along slopes of different shapes has numerous areas of application to field conditions. For a shallow soil, they indicate where terraces or other erosion control measures must be applied to save the limited few inches of valuable topsoil. For areas above reservoirs or other structures that must be protected from excessive sediment, they indicate where and what practices are necessary to reduce sediment to a minimum. For construction sites, such as the slopes around buildings and on highway embankments, they indicate those slope shapes that are preferable for erosion and sedimentation reduction.

As an example of the latter condition, let us consider a large commercial building constructed on a sloping hillside as illustrated in Figure 12. To keep the main floor level, the area will be reshaped so that the slope below the building will be 400 feet long with an average steepness of 5 percent from the edge of the building to a residential area beyond the base of the slope. Grass is desired on this slope, but the fill is so poor that the top several inches will be heavily fertilized and conditioned with other expensive additives to encourage a good stand. Beyond the slope, the residential area has ditches and storm sewers that can adequately carry the runoff but can handle little eroded sediment. With a uniform slope from the building to the 400-foot location, nearly 80 tons of sediment per hundred feet of slope width may be expected annually from this slope until cover is established (Bedford silt loam, southern Indiana). The expected average depth of erosion near the base of the slope will be nearly one inch annually. Besides causing a sediment problem below, this may be excessive for proper establishment of the cover, since rills may be considerably deeper where the water has concentrated and since the seeded grass will be within the top 1/4 inch of soil when sowed. For a complex slope shape on this same area, the sediment loss will be low, but the average depth of erosion will be greater than 1 inch per year near the middle of the slope length until cover is established. However, by using a concave slope shape, the sediment loss from the area will be low, and the depth of erosion will also be much shallower. Therefore, this analysis strongly indicates that for sites such as described, some form of a concave profile would be much less erosive than a uniform or complex slope as commonly used. However, any of the above three would be greatly preferable to a pronounced convex slope.

Summary and Conclusions

The land surface profiles developed by successive periods of erosion were studied for uniform, concave, convex, and complex slope shapes with initial steepnesses averaging 5 and 10 percent. Large differences in maximum sediment load, sediment carried beyond the toe of the slope, eroded depth, and subsequent slope profile occurred for the different shapes.

The concave shape had the least depth of erosion and sediment load, and its shape was changed the least as erosion progressed. The convex shape had the greatest erosion depth and sediment load. For the uniform and complex shapes, erosion depth was more for the complex, but sediment load off the toe was higher for the uniform slope. All initial shapes developed toward dominantly concave profiles as erosion progressed.

Two forms of the erosion relationship for length and steepness of slope were studied. They showed little difference in the sediment loads, erosion depths, and profile changes predicted along the various slope shapes for the steepnesses studied. The major difference was for the flat portion beyond the base of the slopes, where the Smith-Wischmeier equation (6) predicted more erosion than the Zingg equation (9).

The introduction of critical limits of slope steepness and length (below which erosion was not appreciable) into the erosion relationships predicted profiles that more closely resembled natural field slopes. With critical limits, erosion near the top of the slope was less, and the movement of soil ceased closer to the toe of the slope.

The dominant conclusion from the study is that concave slopes erode less along their lengths, produce less sediment, and change shape less than comparable slopes of other shapes. Where land is being reshaped, the use of a concave profile, at least at the lower portions, will reduce erosion and sediment problems.

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TABLE I

SAMPLE COMPUTER PROGRAM OUTPUT FOR A COMPLEX SLOPE USING ZINGG'S EQUATION

Average steepness - 5%   Slope length increment - 10 feet

Part A (First Erosion Period)

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 SLOPE    SLOPE       PROFILE    PROFILE    SEDIMENT   DEPTH OF   PROFILE
 LENGTH   STEEPNESS     0          0        LOAD       EROSION       1

  FT       FT/FT        FT         FT       TON/FT       FT          FT
                       DEPTH      DEPTH     OF WIDTH                DEPTH
  0.      0.          0.         0.          0.        0.          0.
 10.00    0.00615     0.0308     0.0308      0.0001    0.00060     0.0314
 20.00    0.01227     0.1231     0.1231      0.0006    0.00184     0.1249
 30.00    0.01831     0.2763     0.2763      0.0019    0.00377     0.2801
 40.00    0.02424     0.4894     0.4894      0.0044    0.00632     0.4957
 50.00    0.03002     0.7612     0.7612      0.0082    0.00939     0.7706
 60.00    0.03562     1.0899     1.0899      0.0138    0.01287     1.1028
 70.00    0.04099     1.4736     1.4736      0.0211    0.01665     1.4903
 80.00    0.04612     1.9098     1.9098      0.0304    0.02062     1.9304
 90.00    0.05095     2.3960     2.3960      0.0417    0.02463     2.4206
100.00    0.05547     2.9289     2.9289      0.0550    0.02859     2.9575
110.00    0.05966     3.5055     3.5055      0.0703    0.03233     3.5378
120.00    0.06347     4.1222     4.1222      0.0874    0.03571     4.1579
130.00    0.06689     4.7750     4.7750      0.1060    0.03867     4.8137
140.00    0.06991     5.4601     5.4601      0.1260    0.04103     5.5011
150.00    0.07249     6.1732     6.1732      0.1471    0.04267     6.2159
160.00    0.07462     6.9099     6.9099      0.1687    0.04353     6.9534
170.00    0.07629     7.6656     7.6656      0.1906    0.04353     7.7091
180.00    0.07749     8.4357     8.4357      0.2122    0.04260     8.4783
190.00    0.07821     9.2154     9.2154      0.2332    0.04071     9.2561
200.00    0.07846    10.0000    10.0000      0.2529    0.03780    10.0378
210.00    0.07822    10.7846    10.7846      0.2710    0.03386    10.8185
220.00    0.07749    11.5644    11.5644      0.2868    0.02894    11.5933
230.00    0.07629    12.3345    12.3345      0.2999    0.02314    12.3576
240.00    0.07462    13.0902    13.0902      0.3099    0.01647    13.1067
250.00    0.07248    13.8269    13.8269      0.3164    0.00902    13.8359
260.00    0.06990    14.5399    14.5399      0.3190    0.00101    14.5409
270.00    0.06690    15.2250    15.2250      0.3174   -0.00754    15.2175
280.00    0.06347    15.8779    15.8779      0.3114   -0.01643    15.8615
290.00    0.05966    16.4945    16.4945      0.3010   -0.02537    16.4691
300.00    0.05548    17.0711    17.0711      0.2861   -0.03424    17.0369
310.00    0.05095    17.6041    17.6041      0.2667   -0.04279    17.5613
320.00    0.04612    18.0902    18.0902      0.2433   -0.05068    18.0395
330.00    0.04100    18.5264    18.5264      0.2161   -0.05767    18.4687
340.00    0.03562    18.9101    18.9101      0.1856   -0.06346    18.8466
350.00    0.03003    19.2388    19.2388      0.1526   -0.06759    19.1712
360.00    0.02424    19.5106    19.5106      0.1180   -0.06957    19.4410
370.00    0.01831    19.7237    19.7237      0.0830   -0.06865    19.6550
380.00    0.01227    19.8769    19.8769      0.0493   -0.06350    19.8134
390.00    0.00615    19.9692    19.9692      0.0195   -0.04643    19.9228
400.00    0.00154    20.0000    20.0000      0.0029   -0.01952    19.9805
410.00    0.         20.0000    20.0000      0.       -0.00291    19.9971
420.00    0.         20.0000    20.0000      0.        0.         20.0000
430.00    0.         20.0000    20.0000      0.        0.         20.0000
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TABLE I

Part B (Fifty-first Erosion Period)

SLOPE LENGTH FT	SLOPE STEEPNESS FT/FT	PROFILE 0 FT DEPTH	PROFILE 50 FT DEPTH	SEDIMENT LOAD TON/FT OF WIDTH	DEPTH OF EROSION FT	PROFILE 51 FT DEPTH
0.	0.	0.	0.	0.	0.	0.
10.00	0.01330	0.0308	0.0794	0.0002	0.00151	0.0809
20.00	0.02382	0.1231	0.2659	0.0015	0.00420	0.2701
30.00	0.03336	0.2763	0.5558	0.0044	0.00776	0.5635
40.00	0.04146	0.4894	0.9332	0.0093	0.01157	0.9448
50.00	0.04826	0.7612	1.3850	0.0160	0.01527	1.4003
60.00	0.05385	1.0899	1.8983	0.0245	0.01860	1.9169
70.00	0.05836	1.4736	2.4619	0.0346	0.02140	2.4833
80.00	0.06192	1.9098	3.0656	0.0459	0.02359	3.0892
90.00	0.06463	2.3960	3.7003	0.0582	0.02513	3.7255
100.00	0.06658	2.9289	4.3581	0.0711	0.02604	4.3842
110.00	0.06788	3.5055	5.0320	0.0842	0.02635	5.0583
120.00	0.06861	4.1222	5.7158	0.0974	0.02610	5.7419
130.00	0.06882	4.7750	6.4041	0.1103	0.02534	6.4294
140.00	0.06860	5.4601	7.0923	0.1228	0.02413	7.1164
150.00	0.06800	6.1732	7.7762	0.1345	0.02255	7.7987
160.00	0.06707	6.9099	8.4523	0.1453	0.02064	8.4729
170.00	0.06585	7.6656	9.1175	0.1551	0.01848	9.1360
180.00	0.06439	8.4357	9.7693	0.1638	0.01611	9.7854
190.00	0.06273	9.2154	10.4054	0.1712	0.01361	10.4190
200.00	0.06089	10.0000	11.0239	0.1774	0.01100	11.0349
210.00	0.05891	10.7846	11.6232	0.1822	0.00836	11.6316
220.00	0.05682	11.5644	12.2022	0.1857	0.00571	12.2079
230.00	0.05463	12.3345	12.7596	0.1879	0.00309	12.7627
240.00	0.05238	13.0902	13.2948	0.1888	0.00054	13.2954
250.00	0.05007	13.8269	13.8072	0.1885	-0.00191	13.8053
260.00	0.04772	14.5399	14.2962	0.1869	-0.00423	14.2919
270.00	0.04536	15.2250	14.7616	0.1842	-0.00641	14.7552
280.00	0.04300	15.8779	15.2034	0.1805	-0.00843	15.1950
290.00	0.04064	16.4945	15.6215	0.1758	-0.01026	15.6113
300.00	0.03830	17.0711	16.0161	0.1702	-0.01191	16.0042
310.00	0.03599	17.6041	16.3875	0.1639	-0.01336	16.3741
320.00	0.03371	18.0902	16.7359	0.1569	-0.01460	16.7212
330.00	0.03148	18.5264	17.0617	0.1493	-0.01564	17.0461
340.00	0.02931	18.9101	17.3655	0.1412	-0.01648	17.3490
350.00	0.02719	19.2388	17.6479	0.1328	-0.01711	17.6307
360.00	0.02514	19.5106	17.9093	0.1241	-0.01754	17.8918
370.00	0.02315	19.7237	18.1506	0.1153	-0.01778	18.1328
380.00	0.02124	19.8769	18.3724	0.1064	-0.01783	18.3546
390.00	0.01941	19.9692	18.5755	0.0975	-0.01771	18.5578
400.00	0.01765	20.0000	18.7606	0.0886	-0.01742	18.7432
410.00	0.01598	20.0000	18.9286	0.0800	-0.01699	18.9116
420.00	0.01439	20.0000	19.0803	0.0717	-0.01642	19.0639
430.00	0.01289	20.0000	19.2165	0.0636	-0.01572	19.2007
440.00	0.01147	20.0000	19.3381	0.0559	-0.01491	19.3232
450.00	0.01014	20.0000	19.4459	0.0487	-0.01402	19.4319
460.00	0.00890	20.0000	19.5410	0.0419	-0.01304	19.5279
470.00	0.00775	20.0000	19.6240	0.0357	-0.01201	19.6120
480.00	0.00668	20.0000	19.6960	0.0299	-0.01094	19.6850
490.00	0.00570	20.0000	19.7577	0.0247	-0.00984	19.7478

TABLE I

Part C (Two hundred-first Erosion Period)

SLOPE LENGTH FT	SLOPE STEEPNESS FT/FT	PROFILE 0 FT DEPTH	PROFILE 200 FT DEPTH	SEDIMENT LOAD TON/FT OF WIDTH	DEPTH OF EROSION FT	PROFILE 201 FT DEPTH
0.	0.	0.	0.	0.	0.	0.
10.00	0.07685	0.0308	0.7602	0.0027	0.00775	0.7680
20.00	0.07669	0.1231	1.5371	0.0077	0.01098	1.5480
30.00	0.07473	0.2763	2.2940	0.0137	0.01260	2.3066
40.00	0.07274	0.4894	3.0317	0.0203	0.01350	3.0452
50.00	0.07052	0.7612	3.7488	0.0272	0.01383	3.7627
60.00	0.06823	1.0899	4.4421	0.0342	0.01383	4.4560
70.00	0.06594	1.4736	5.1134	0.0411	0.01356	5.1270
80.00	0.06364	1.9098	5.7609	0.0477	0.01311	5.7740
90.00	0.06140	2.3960	6.3863	0.0542	0.01254	6.3988
100.00	0.05919	2.9289	6.9889	0.0603	0.01186	7.0007
110.00	0.05704	3.5055	7.5701	0.0660	0.01112	7.5812
120.00	0.05495	4.1222	8.1297	0.0714	0.01033	8.1401
130.00	0.05291	4.7750	8.6690	0.0764	0.00951	8.6785
140.00	0.05093	5.4601	9.1880	0.0809	0.00868	9.1967
150.00	0.04902	6.1732	9.6877	0.0850	0.00784	9.6955
160.00	0.04716	6.9099	10.1684	0.0887	0.00700	10.1754
170.00	0.04536	7.6656	10.6308	0.0920	0.00617	10.6370
180.00	0.04361	8.4357	11.0755	0.0949	0.00536	11.0809
190.00	0.04192	9.2154	11.5031	0.0974	0.00457	11.5077
200.00	0.04029	10.0000	11.9140	0.0995	0.00380	11.9178
210.00	0.03870	10.7846	12.3088	0.1012	0.00306	12.3119
220.00	0.03717	11.5644	12.6881	0.1025	0.00235	12.6904
230.00	0.03569	12.3345	13.0523	0.1035	0.00166	13.0539
240.00	0.03425	13.0902	13.4019	0.1042	0.00101	13.4029
250.00	0.03287	13.8269	13.7374	0.1046	0.00039	13.7378
260.00	0.03152	14.5399	14.0592	0.1046	-0.00020	14.0590
270.00	0.03022	15.2250	14.3679	0.1044	-0.00075	14.3671
280.00	0.02897	15.8779	14.6637	0.1038	-0.00127	14.6624
290.00	0.02775	16.4945	14.9472	0.1031	-0.00176	14.9455
300.00	0.02658	17.0711	15.2188	0.1021	-0.00221	15.2166
310.00	0.02544	17.6041	15.4788	0.1009	-0.00263	15.4762
320.00	0.02434	18.0902	15.7276	0.0995	-0.00302	15.7246
330.00	0.02328	18.5264	15.9657	0.0979	-0.00338	15.9623
340.00	0.02226	18.9101	16.1933	0.0961	-0.00370	16.1896
350.00	0.02127	19.2388	16.4108	0.0942	-0.00400	16.4068
360.00	0.02031	19.5106	16.6186	0.0921	-0.00427	16.6143
370.00	0.01938	19.7237	16.8170	0.0899	-0.00451	16.8125
380.00	0.01849	19.8769	17.0063	0.0876	-0.00472	17.0016
390.00	0.01763	19.9692	17.1868	0.0852	-0.00490	17.1819
400.00	0.01680	20.0000	17.3589	0.0827	-0.00506	17.3538
410.00	0.01599	20.0000	17.5227	0.0801	-0.00519	17.5175
420.00	0.01522	20.0000	17.6787	0.0775	-0.00530	17.6734
430.00	0.01447	20.0000	17.8271	0.0748	-0.00539	17.8217
440.00	0.01375	20.0000	17.9682	0.0721	-0.00546	17.9627
450.00	0.01306	20.0000	18.1021	0.0693	-0.00550	18.0966
460.00	0.01239	20.0000	18.2293	0.0666	-0.00553	18.2238
470.00	0.01175	20.0000	18.3499	0.0638	-0.00553	18.3444
480.00	0.01113	20.0000	18.4642	0.0610	-0.00552	18.4587
490.00	0.01053	20.0000	18.5724	0.0583	-0.00549	18.5669

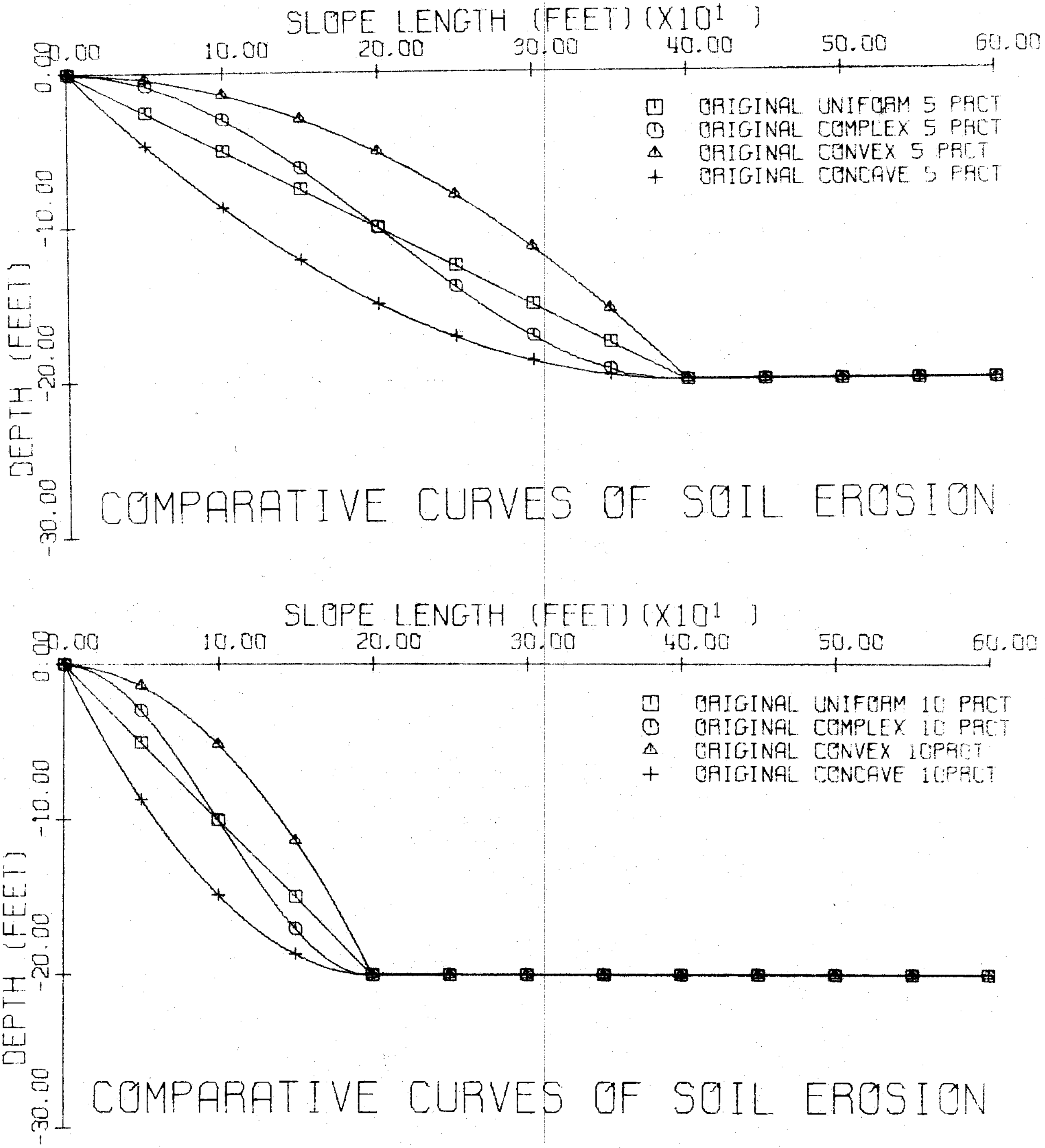


FIGURE 1. Four initial slope shapes - uniform, complex, convex, and concave - that were studied to determine the effects of successive periods of erosion. Average slope steepness is 5% in the upper graph and 10% in the lower graph. Elevation change is 20 feet, so sloping length is 400 feet in the upper graph and 200 feet in the lower graph. Note that a flat area was assumed beyond the toe of the slopes.

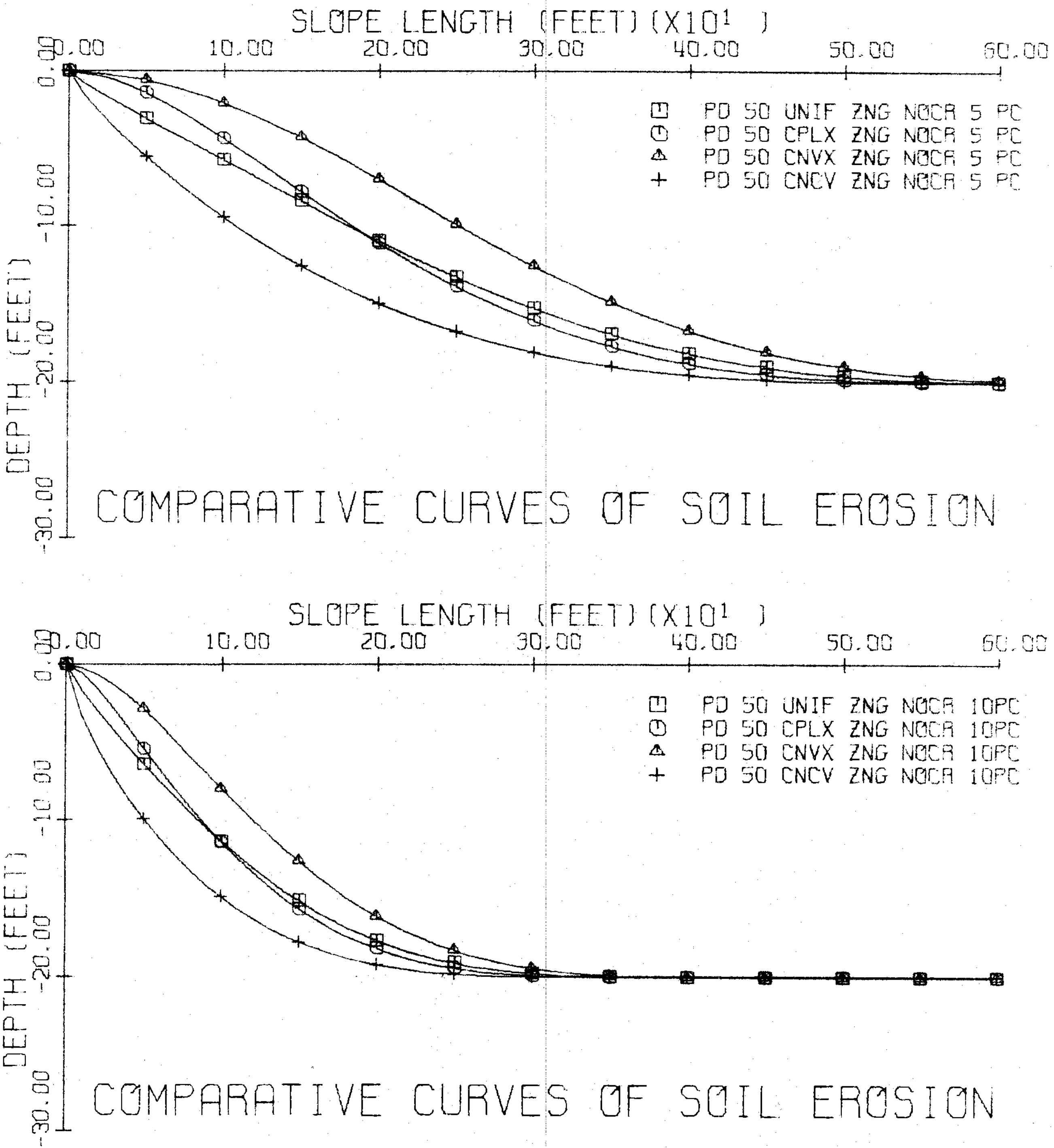


FIGURE 2. Slope shape profiles developed from the initial shapes in Figure 1 during 50 periods of erosion as predicted by the Zingg equation.

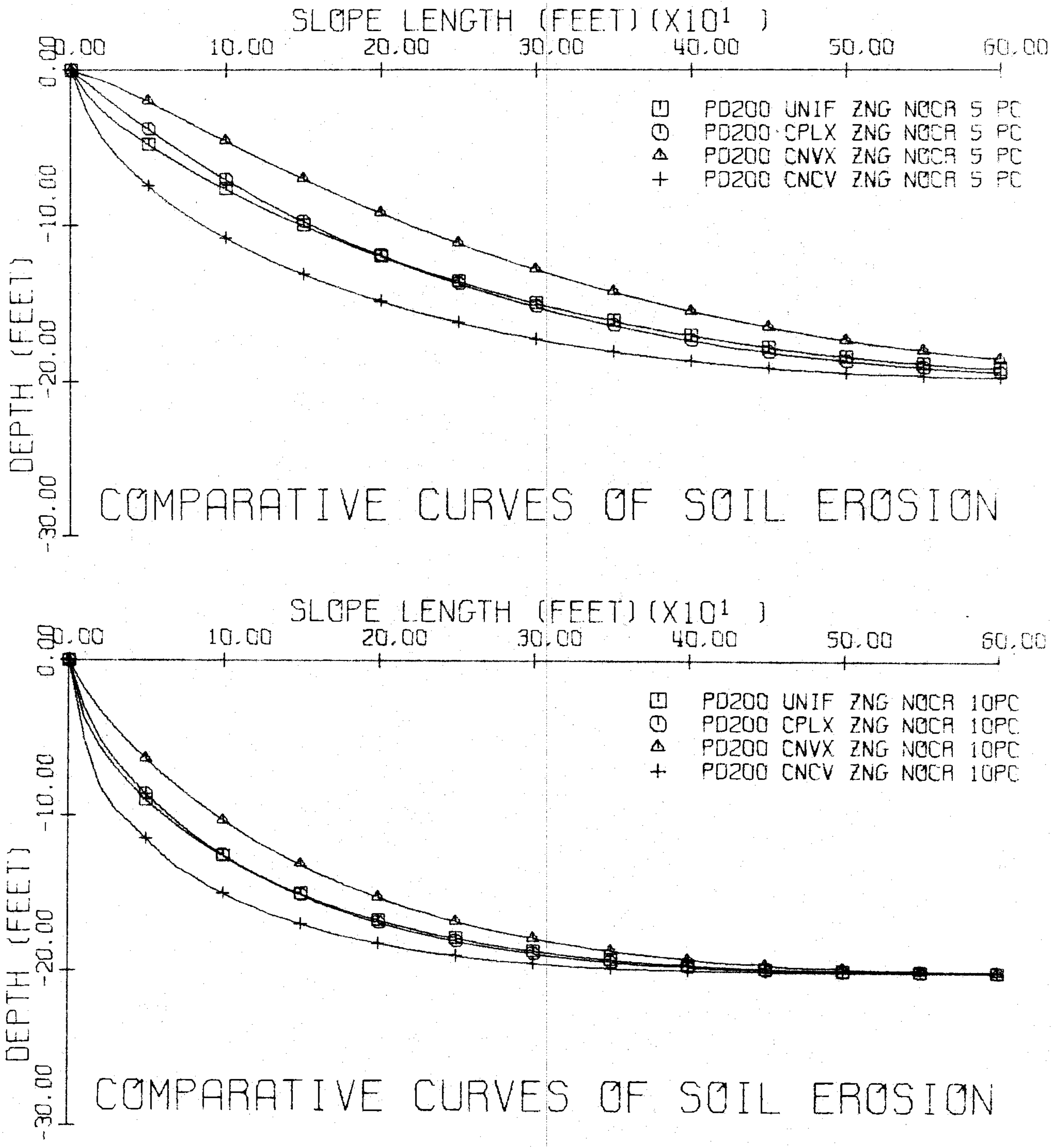


FIGURE 3. Slope shape profiles developed from the initial shapes in Figure 1 by 200 periods of erosion as predicted by the Zingg equation.

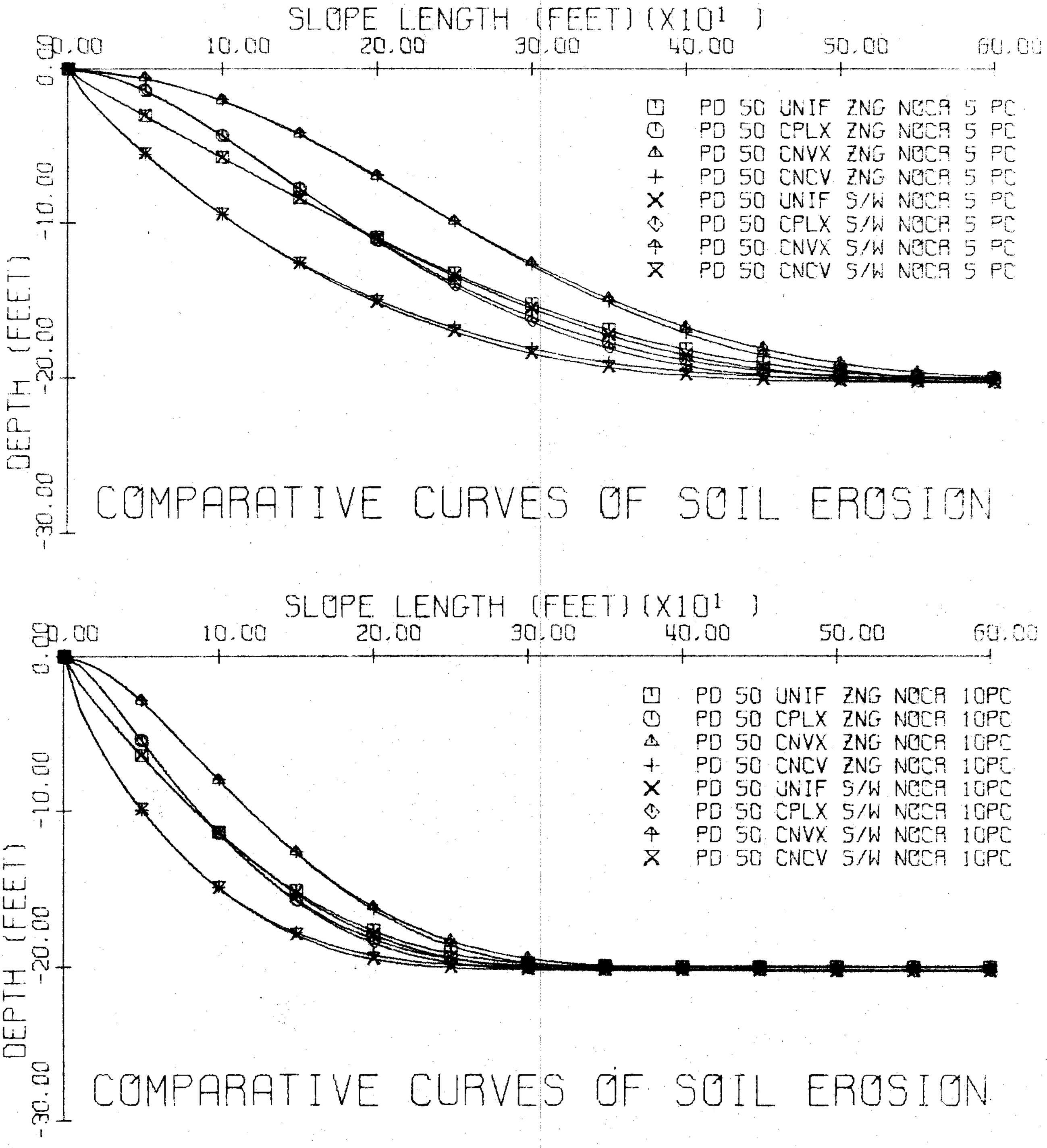


FIGURE 4. Comparison of the slope shape profiles predicted by the Zingg and Smith-Wischmeier equations after 50 periods of erosion. The Zingg profiles are the upper of each pair where they separate near the toe of the initial slopes.

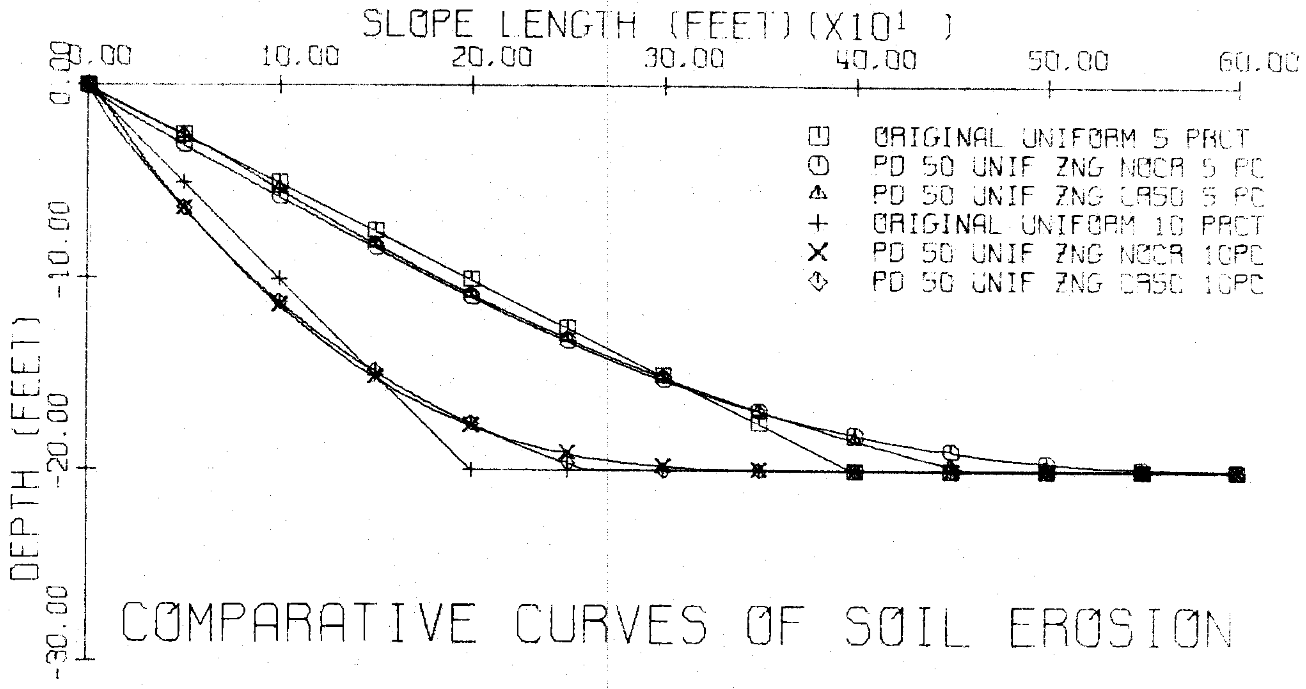


FIGURE 5. Slope shape profiles developed during 50 periods of erosion for 5% and 10% initially uniform slopes. Shown are the original shapes, the shapes predicted by Zingg's equation form, and the shapes predicted using a modified form of Zingg's equation that included critical values of slope steepness.

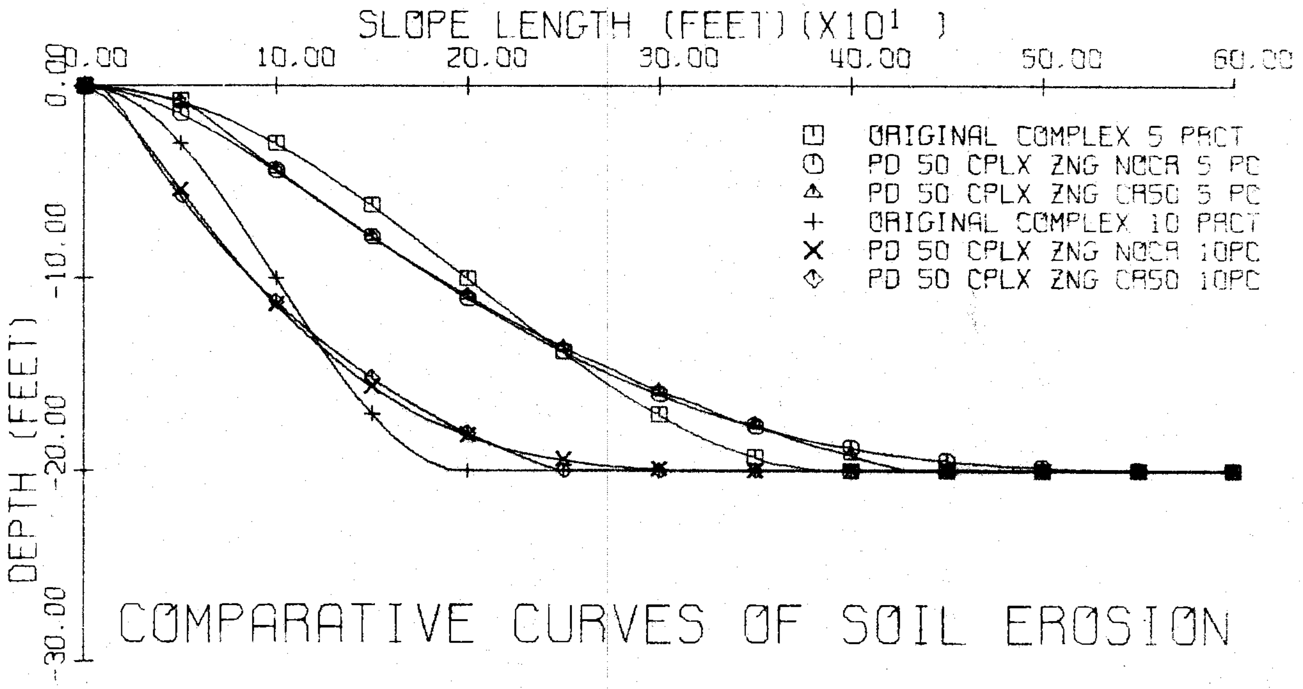


FIGURE 6. Same as Figure 5 for initially complex slopes.

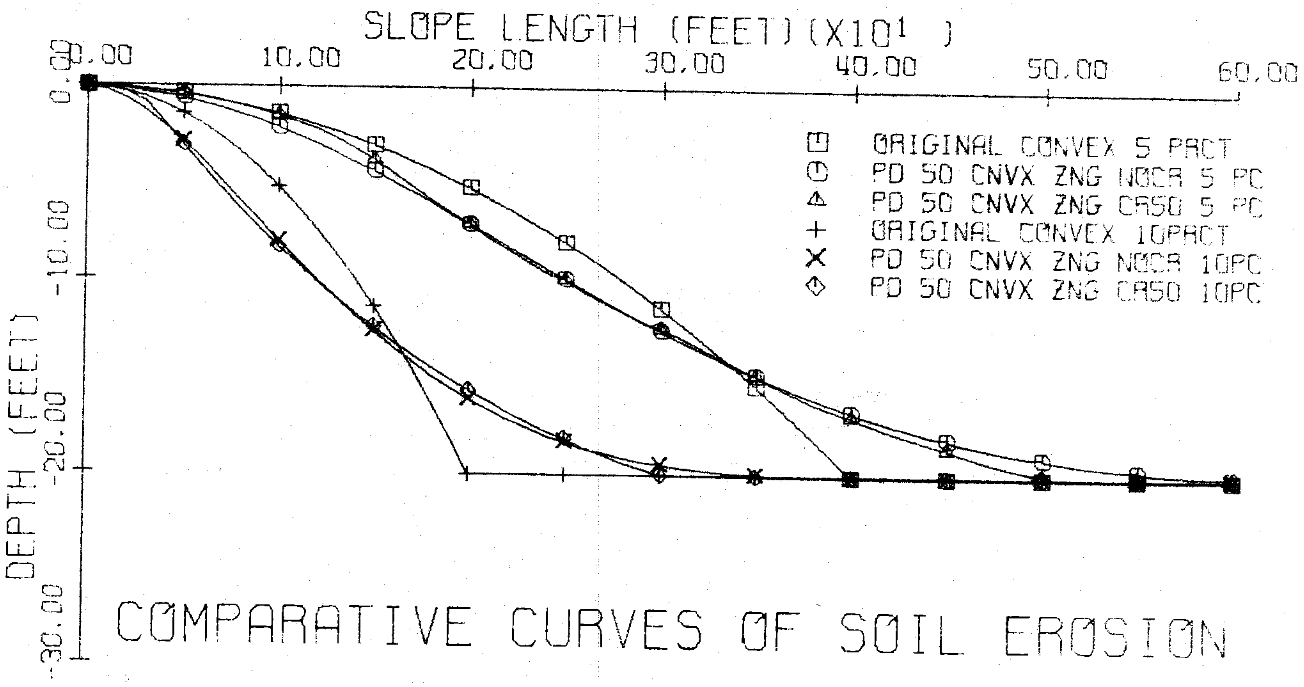


FIGURE 7. Same as Figure 5 for initially convex slopes.

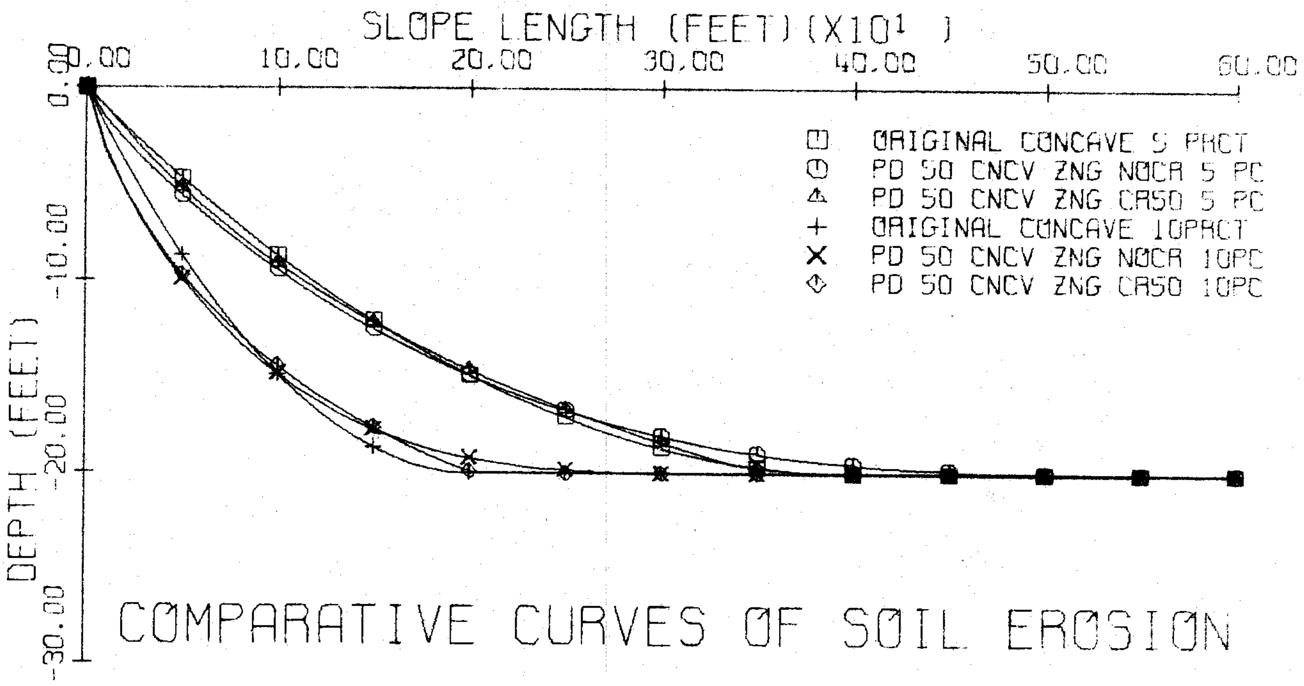


FIGURE 8. Same as Figure 5 for initially concave slopes.

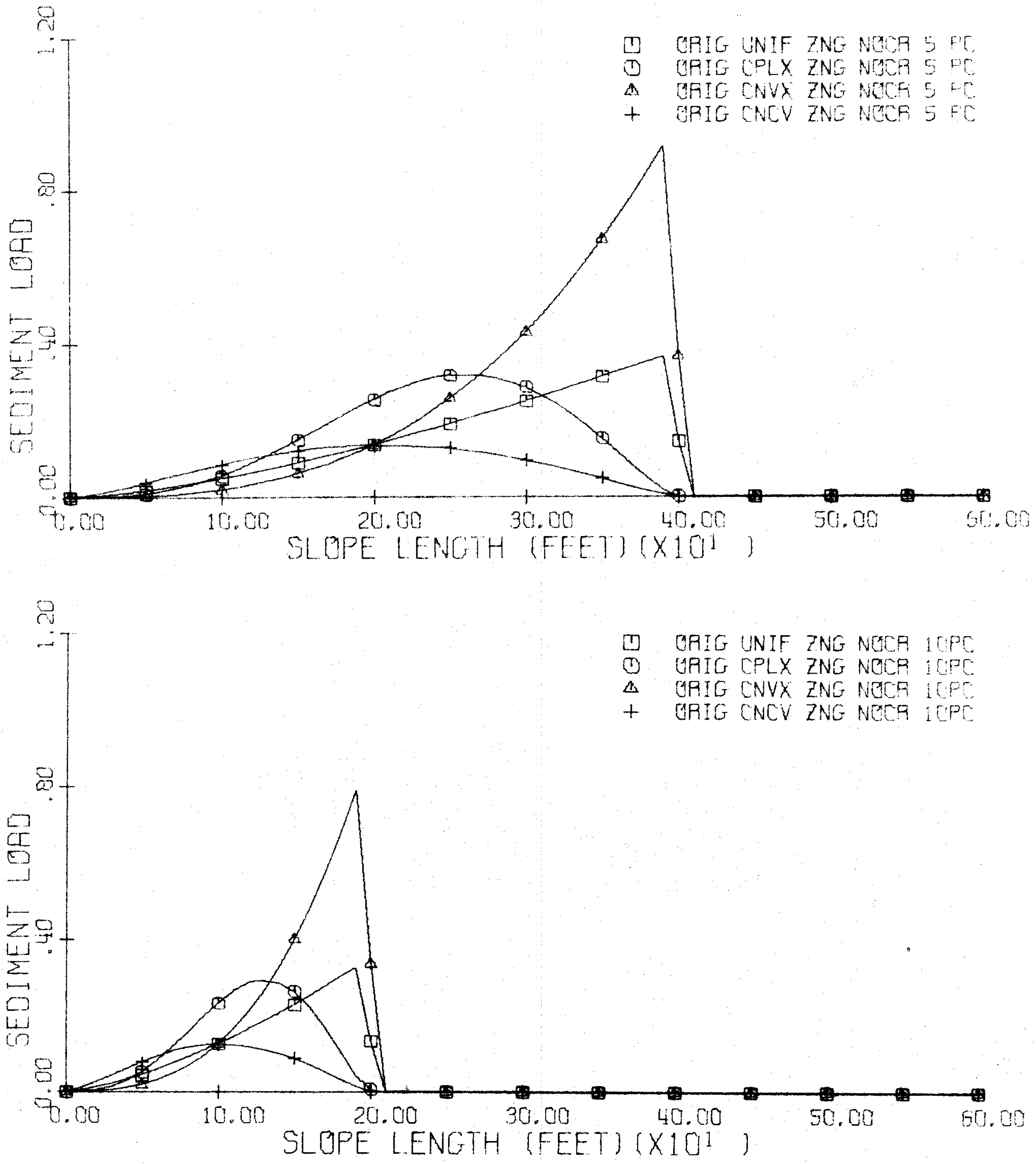


FIGURE 9. Sediment load or total erosion (tons per foot of slope width) along the four original slope shapes of Figure 1 during their first period of erosion as predicted by Zingg's equation. Where the curves have positive slopes, the sediment load was increasing and net erosion was occurring. Where negative, deposition was occurring. The steepness at any point along a curve indicates the relative depth of erosion or deposition there.

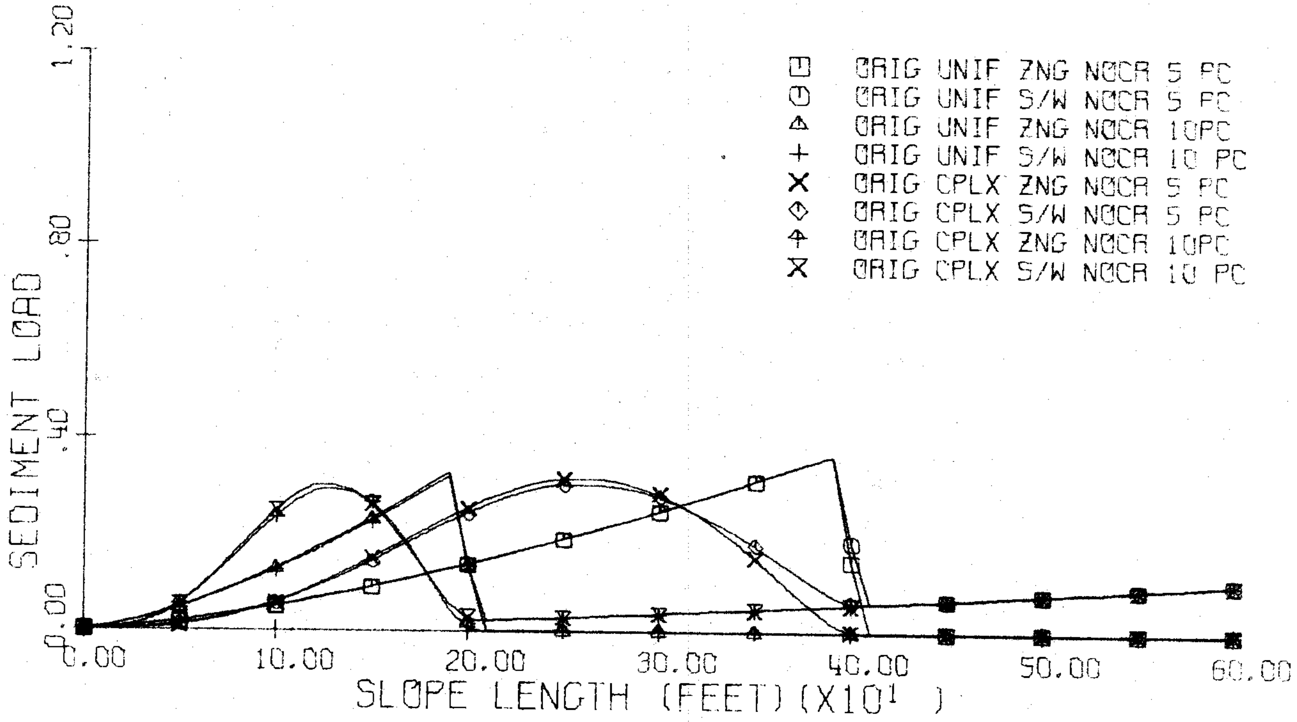
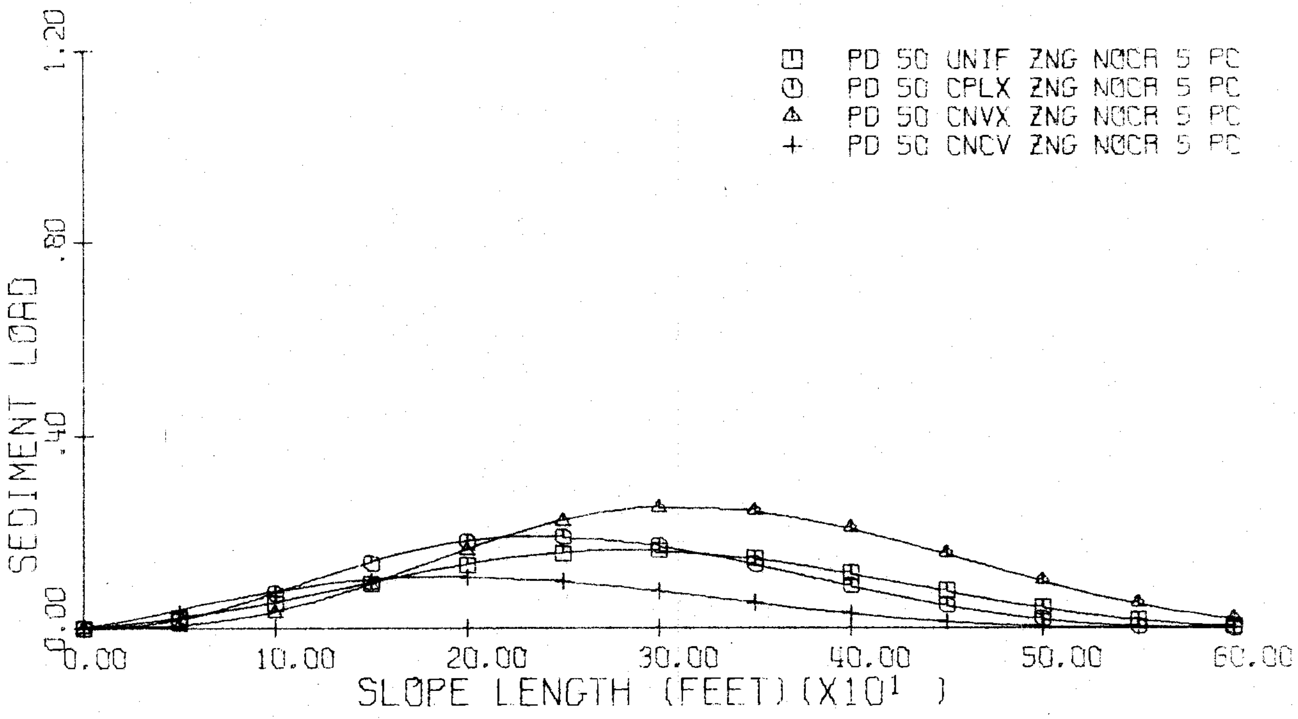


FIGURE 10. Comparison of the sediment loads predicted by the Zingg and Smith-Wischmeier equations during the first erosion period for initially uniform and complex slopes averaging 5 and 10% steepness. Note that the Smith-Wischmeier form predicts erosion beyond the toe of the slope whereas the Zingg form does not.



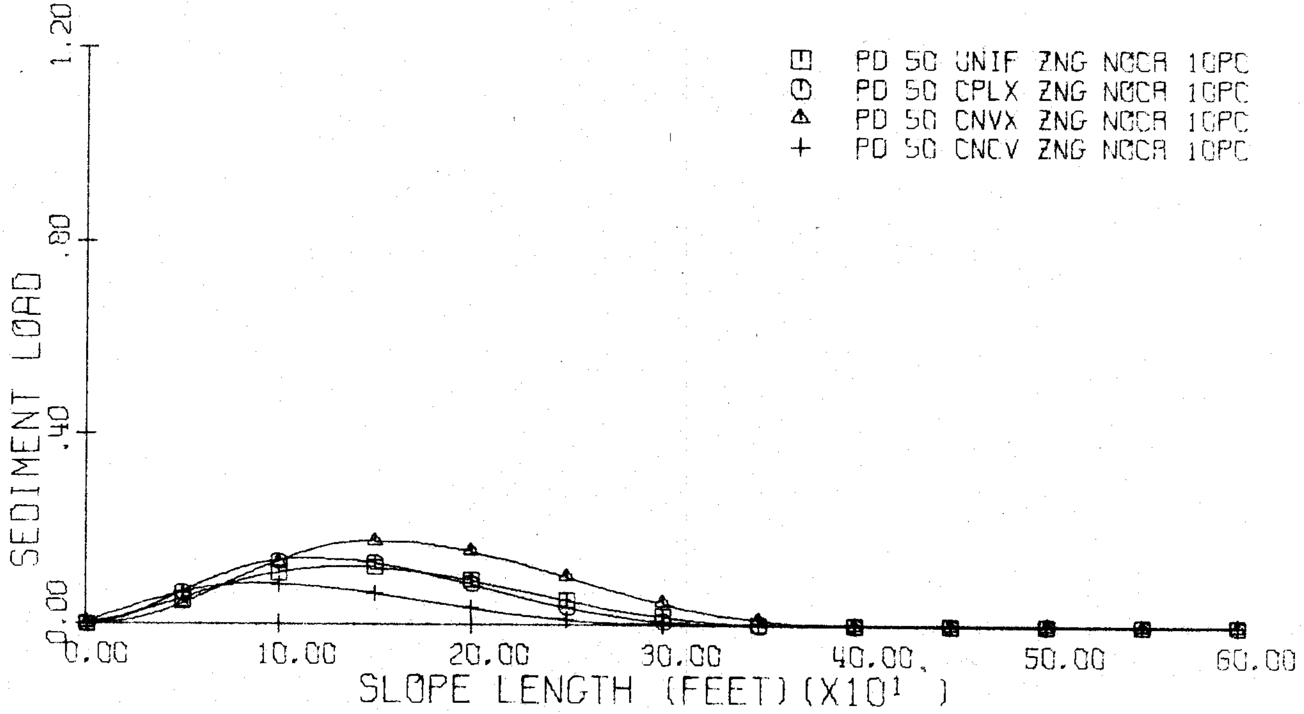


FIGURE 11. Same as Figure 9 for the slope shapes shown in Figure 2 as developed by 50 periods of erosion.

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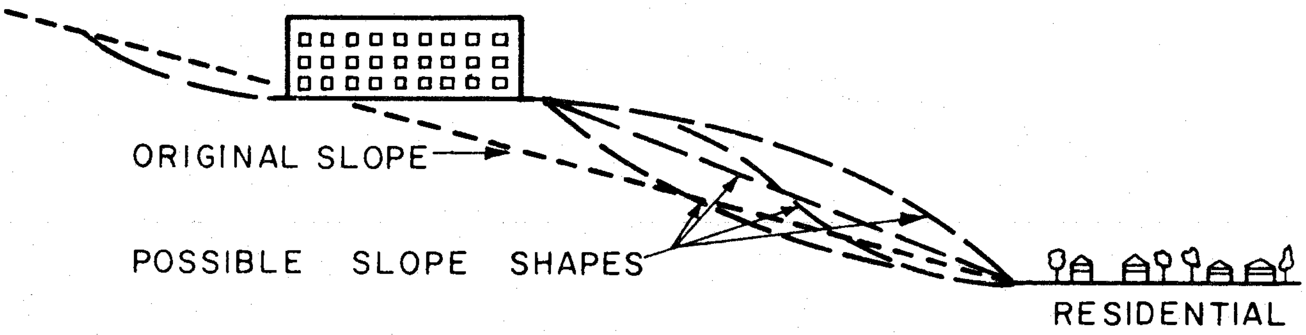

FIGURE 12. Four ways that the area downslope from a construction site might be reshaped. The concave shape will be least erosive along the slope and will produce the least sediment off the end of the slope.