Compressibility of Broken Rock and the Settlement of Rockfills

Compressibilité des roches fragmentées et tassement des remblais rocheux

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SUMMARY

Rockfill dams have been observed to settle from 0.25 per cent to 1 per cent of their height in the first 10 years following construction, and continue thereafter but at a decreasing rate. The plots of settlements as functions of the logarithm of time for 14 rockfill dams were found to approximate straight lines, similar to the secondary compression of soils. Laboratory consolidation tests of broken rock exhibit similar settlement—log time effects, and comparable settlement rates. The laboratory tests show that the rate of settlement is accelerated by both wetting of the rock and by shock. Gradation changes show that the settlement results from crushing of the points of contact between rock fragments. Tests of point fracture under constant load exhibit rapid initial crushing that increases slightly with increasing time, and sudden additional crushing upon wetting, as the water enters the microfissures in the highly stressed contact points.

SOMMAIRE

On note dans les barrages de remblai rocheux des tassements de 0.25 pour cent à 1 pour cent de leur hauteur en dix ans après leur construction, continuant plus lentement par la suite. On trouve que les courbes de tassement de 14 barrages de remblai rocheux approchent des fonctions linéaires du logarithme du temps, similaires aux courbes de compression secondaire. Des essais de consolidation sur des échantillons de roche en laboratoire montrent des effets similaires du temps ainsi que des vitesses de tassement comparables. Les essais révèlent des augmentations des tassements à cause d'immersion ou de choc. Des changements de composition granulométrique montrent que les tassements proviennent de l'écrasement des points de contact des fragments de roche. Des essais de fracture en un point sous charges constantes démontrent des écrasements initiaux rapides, augmentant avec le temps, ainsi que des brusques écrasements additionnels provoqués par l'entrée de l'eau dans les microfissures des points de contact hautement chargés.

ROCKFILLS HAVE BEEN EXTENSIVELY EMPLOYED in dam construction and are being used increasingly for highway embankments. Experience has shown that rockfills settle significantly during construction and that the settlement continues indefinitely, but at an ever decreasing rate. Although there has been considerable speculation about the cause of rockfill settlement, no satisfactory theory for the mechanics of the process or the prediction of settlement is available. The purpose of this research was to analyse the available dam settlement data, to study the mechanism of rockfill settlement by confined compression tests in the laboratory, and to develop a hypothesis for the settlement behaviour that would be useful in estimating the continuing settlement of rockfills and developing construction procedures that could minimize settlements.

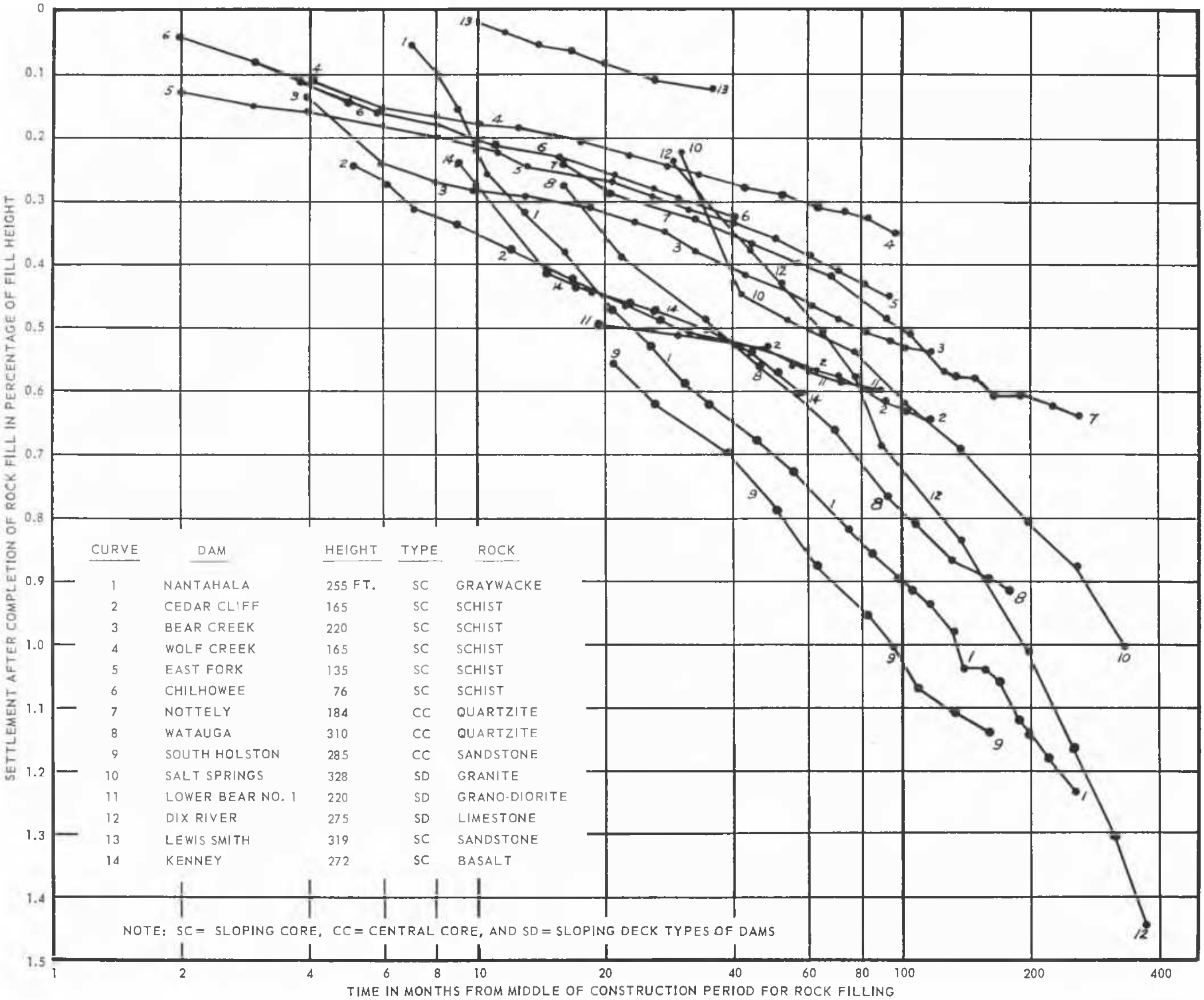
OBSERVED SETTLEMENT OF ROCKFILL DAMS

Extensive information on settlement was presented in 1958 in the Symposium of the American Society of Civil Engineers on rockfill dams. The data on the settlement taking place during construction are fragmentary because of the difficulties of making measurements. Baumann (1960) observed construction settlements from 6 to 18 per cent of the height of dumped rockfills in which little sluicing had been permitted, based on the volume of the rock as placed compared to the volume of the completed dam. Cary (1960) reported construction settlements of intermediate levels of the Mud Mountain Dam to be 1 to 3 per cent of the height.

Settlements occurring after construction was completed have been reported in sufficient detail by Growdon (1960), Leonard and Raine (1960), Schmidt (1960), Steele and Cooke (1960), Elliott (1963), and Hayes (1964) that analyses of time-rate of continuing settlement are possible. A plot of these data with the settlement of the dam crest as a function of the logarithm of time is shown on Fig. 1. The point of zero time in each case was indefinite because the lowest lifts began to settle before the upper ones were placed. The zero time for the plot was the estimated date at which half the fill was completed, based on the published construction schedules.

The curves show a surprisingly narrow range of settlements from 0.25 to about 1 per cent of the height in 10 years. The amount does not appear to be related to the dam height, the rock, or the dam type (i.e. central core, etc.). Instead, the only significant factor appears to be the method of construction. The dam with the greatest settlement, Dix River, was dumped with limited sluicing; that with the least settlement, Lewis Smith, was largely compacted by rolling combined with sluicing. The later ALCOA dams, Wolf Creek, East Fork, Bear Creek, and Chilhowee, which reflect better construction techniques gained by experience, have settled less than the earlier Nantahala and Cedar Cliff dams.

Although the settlement-log time data of Fig. 1 exhibit some irregularities, as might be expected with the varying water loadings, all except Dix River can be approximated by straight lines. This makes it possible to estimate future



CURVE	DAM	HEIGHT	TYPE	ROCK
1	NANTAHALA	255 FT.	SC	GRAYWACKE
2	CEDAR CLIFF	165	SC	SCHIST
3	BEAR CREEK	220	SC	SCHIST
4	WOLF CREEK	165	SC	SCHIST
5	EAST FORK	135	SC	SCHIST
6	CHILHOWEE	76	SC	SCHIST
7	NOTTELY	184	CC	QUARTZITE
8	WATAUGA	310	CC	QUARTZITE
9	SOUTH HOLSTON	285	CC	SANDSTONE
10	SALT SPRINGS	328	SD	GRANITE
11	LOWER BEAR NO. 1	220	SD	GRANO-DIORITE
12	DIX RIVER	275	SD	LIMESTONE
13	LEWIS SMITH	319	SC	SANDSTONE
14	KENNEY	272	SC	BASALT

NOTE: SC= SLOPING CORE, CC= CENTRAL CORE, AND SD= SLOPING DECK TYPES OF DAMS

FIG. 1. Observed settlement of rockfill dams after completion of construction (after Growdon (1960), Hayes (1964), Leonard and Raine (1960), Schmidt (1960), Steele and Cooke (1960)).

settlements by a simple extrapolation, and to express the decreasing rate of settlement by the slope of the line, as described by the parameter α:

$$\Delta H = \alpha(\log t_2 - \log t_1). \tag{1}$$

In this equation ΔH is the settlement in per cent of the fill height that occurred between the times t_1 and t_2 from the beginning of the period of settlement (the date when half the fill was completed). The values of α for Fig. 1 range from about 0.2 for Wolf Creek, East Fork, Chilhowee, Lower Bear No. 1, and Lewis Smith to about 0.7 for Nantahala, South Holston, and Salt Springs. Only Dix River, with an α of 1.05, is outside of the range.

A number of explanations have been offered for the cause of rockfill settlement and for the benefits of sluicing in reducing settlement. Terzaghi (1960) attributed the continuing settlement to the progressive reorientation of the particles in finding more stable positions, similar to the compression of sand. He suggested that sluicing contributes to a more dense structure by weakening the rock and permitting the pieces to break and compact; therefore subsequent settlement is less. On the other hand, Snethlage, *et al.* (1960) state that the major benefit of sluicing is to wash the fines from between the points of contact of the larger rock and thereby permit the larger rock to develop more firm contacts. They attribute the continuing settlement to crushing of the rock edges and points, and the consequent readjustment of the pieces. None of these hypotheses can be directly verified by field observations, and for this reason laboratory tests were undertaken to study the mechanics of rockfill settlement under more controlled conditions.

LABORATORY STUDIES OF ROCK COMPRESSION

Compression tests were performed on broken rock similar to the one-dimensional consolidation test of soils. The apparatus consisted of a steel cylinder 7.5 in. in diameter and 4 in. deep in which the rock fragments were placed, and a 1.5-in.-thick steel piston (tapered so as to permit some tilting without binding) to which the load was applied. Constant loads up to 32,500 psf were supplied by a pneumatically

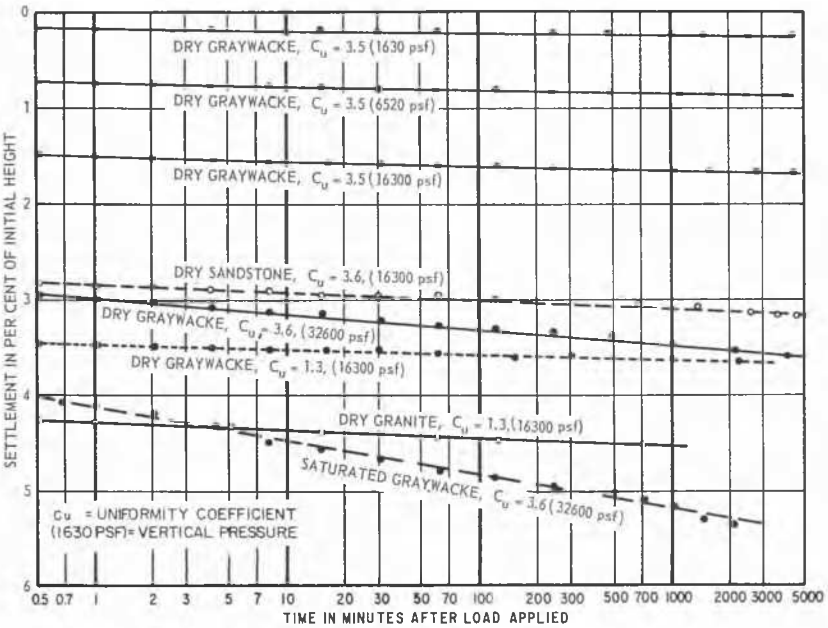


FIG. 2. Settlement–log time curves for laboratory confined compression tests of broken rock for constant vertical pressures applied in increments.

loaded bellows. The rock could be flooded or jetted at a pressure of 300 psi by 1/16-in. orifices in the side of the cylinder and drained through perforations in the bottom.

Three different rocks were utilized: a granite, graywacke (feldspathic quartzite) from Nantahala Dam, and sandstone from Lewis Smith Dam. The graywacke strength was 26,000 psi wet; the others were unchanged by wetting, with unconfined compressive strengths of 12,000, 31,000, and 9,000 psi dry. The rocks were broken by hammer and chisel to obtain fresh fractures, a maximum size of 3.8 cm, and uniformity coefficients of 1.3 and 3.5. Epoxy cement was placed between the end plates and the broken rock to distribute the load uniformly and to prevent local crushing of the rock against the rigid steel surfaces. The samples were loaded in increments, each of which was maintained constant for about 3 days after which a greater load was applied. Settlement readings were made at increasing time intervals, similar to those of a soil consolidation test, and were corrected for the compression of the apparatus.

Representative settlement log-time curves are given on Fig. 2. They indicate rapid initial settlement plus continuing settlement that approximates a straight line on the semi-log plot, similar to the observed continuing settlements of dams. The values of α range from 0.02 for the dry graywacke at 1630 psf to 0.35 for the saturated graywacke at 32,600 psf. The rate of settlement increases with increasing load as can be seen by the graywacke (C_u = 3.5) and increases greatly upon saturation. The uniform graywacke settles at a slightly greater rate than the graded. Quite unexpectedly the rates of continuing settlement of all 3 rocks at the same load, 16,300 psf, are nearly the same, although their physical properties are greatly different. The weakest, sandstone, when dry, had an α of 0.09, the slightly stronger granite an α of 0.10, and the much stronger graywacke an α of 0.07. For the range in stresses found in the dams of Fig. 1, up to 45,000 psf, the values of α found in the laboratory tests are of the same order of magnitude (but somewhat smaller) than those exhibited by the dams. Of course, a direct comparison cannot be made because the load increments are different, and certainly neither the field gradations, nor densities, nor environments were reproduced in the laboratory tests.

The settlement–log pressure curves are given in Fig. 3. The shapes are similar to those found for soils, and the amounts similar to those for sands and similar particulate materials. The comparative compressibilities reflect the differences in gradation and rock strength; however, it is surprising that the graded sandstone had nearly the same compressibility as the much stronger but uniform graywacke.

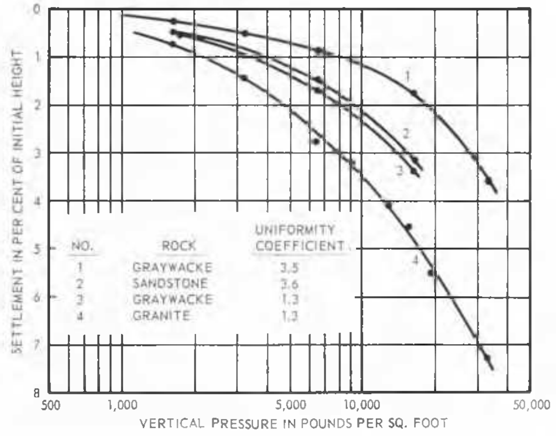


FIG. 3. Settlement–log pressure curves for laboratory confined compression tests on dry broken rock (measured at approximately 4400 minutes or 3 days).

Loading of the rock was followed by popping and grinding sounds, each accompanied by small sudden increases in settlement. Similar sounds have been heard following sudden changes in the water load on dams. Grain size analyses before and after testing showed a significant increase in the fines as a result of compression. There was no visible change in the particle orientation: however, there was no method available for determining this quantitatively.

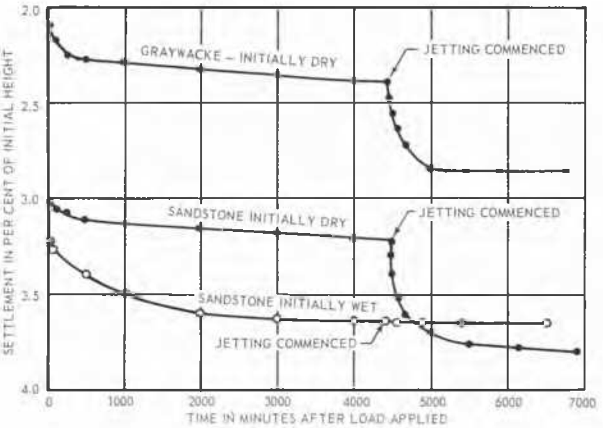


FIG. 4. Effect of jetting dry rock under load and of initial wetting on settlement at 16,300 psf.

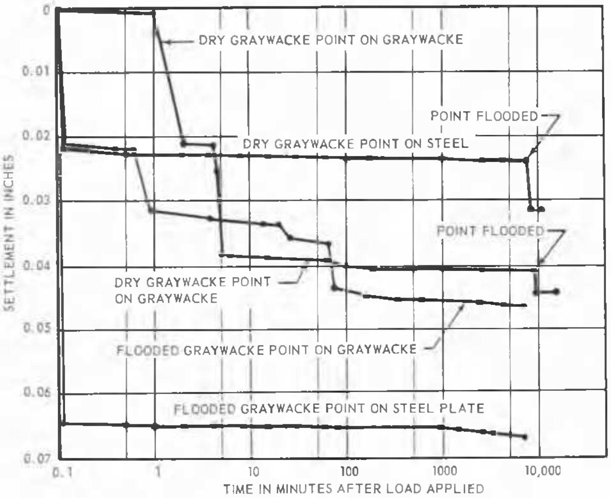


FIG. 5. Time-dependent crushing of rock points, initially dry and subsequently flooded, and initially flooded.

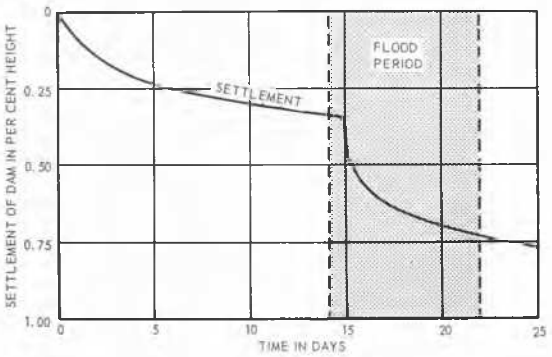


FIG. 6. Effect of a flood on the settlement of the Dix River dam (after Howson, 1939).

The effect of sluicing was investigated by comparative tests of dry, wet, and jetted rock, the partial results of which are illustrated in Fig. 4. When dry rock under load was jetted, the settlement increased immediately by about 20 per cent. Similar increased settlement was produced by merely wetting the rock, without jetting. The increases were the same in both the relatively porous sandstone and the non-porous graywacke. When the rock was initially wet, the initial settlement was greater and comparable to the settlement produced in the dry rock after wetting or jetting. Jetting of the initially wet rock produced no change in the settlement rate.

The local crushing of the points of contact between rock fragments was investigated by loading cylinders of rock, one end of which had been sharpened in the shape of either a pyramid or a wedge. In some cases the points were forced against steel plates; in others against flat ground surfaces of the same rock. The results of a few of the tests are shown in Fig. 5. All exhibit a rather sudden initial settlement when the sharp point is crushed, followed by slowly increasing settlement that approximates a straight line on the settlement–log time plot. In addition the rock point-on-rock tests show sporadic sudden increased crushing that also decreased with time.

The points that were wet crushed more than those that were initially dry. After the points that were initially dry had shown no appreciable movement for a 5-day period, they were inundated. Within 30 minutes at the most and in a fraction of a second in some cases additional crushing developed. The crushing in all cases took place by splitting and spalling of the rock point until the area in contact with the flat surface was increased and cushioned by the spalled material. The addition of an agent to the water that reduced the surface tension to half the normal value increased the amount of additional crushing produced by wetting and reduced the delay (if any) between wetting and added crushing.

The sudden increase in settlement upon wetting is confirmed by observation of the Dix River Dam during the construction, Fig. 6, when a sudden flood saturated the partially completed embankment. Both the laboratory tests and field performance lend weight to the crushing-upon-wetting hypothesis.

CONCLUSIONS

The laboratory tests show that a major mechanism in the settlement of rockfills is the crushing of the highly stressed points of contact between the particles. It is likely that some reorientation of the grains results from the crushing which in turn produces additional settlement.

The rate of continuing settlement is remarkably like secondary compression in clays. The latter, however, is ordinarily attributed to the force systems associated with the clay minerals and their adsorbed water, which cannot be the case in the freshly broken unweathered rock. The continuing settlement of the rock therefore must involve a different mechanism than that for clays or else the present theories for secondary compression are inadequate. The point crushing tests exhibit a time dependence that is presently not explained. The time dependent compression of the mass can be explained by the local crushing of one point which causes a local redistribution of stress and a slight shifting of the particle which in turn brings added crushing at a new location. The number of fresh faces and points subject to crushing becomes less as each point in turn is crushed, and so the rate decreases, a process which can be expressed by a straight line on a semi-log plot.

The amount and rate of settlement found in laboratory tests is comparable to that observed in structures, which indicates that predictions of rockfill settlement from such tests may be feasible.

A major effect of sluicing is to accelerate the crushing of the rock points and thus enable the mass to achieve a low rate of settlement sooner. The acceleration of rock crushing by sluicing was explained by Terzaghi (1960) as a softening of the mineral bonds by wetting, similar to the reduction in rock strength caused by saturation. The effect of wetting observed in the sandstone, which exhibited the same strength wet or dry, and the sudden crushing produced by wetting the impervious graywacke are not adequately explained by bond softening. The authors suspect that the water entering the microfissures produced in the highly stressed contact points causes a local increase in stress and additional failure. The increased amount and speed of crushing on the addition of low surface tension water noted in the latest studies tends to contradict this hypothesis, however, and it must be the subject of further research.

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