Soil Properties of Fort Union Clay Shale

Propriété des argiles schisteuses de Fort Union

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Summary

This paper gives the geological description and discusses the soil classification, laboratory tests (including extra high load consolidation test) on undisturbed samples and field data on the Fort Union clay shale. At Garrison Dam, the largest rolled fill dam in the world, the Fort Union clay shale is the foundation for heavy structures and clay shales from the structural excavation are used in the rolled embankment.

Sommaire

Ce rapport analyse la géologie du barrage de Fort Union et discute la classification du sol, les essais de laboratoire (y compris l'essai de la charge maximum de consolidation sur des échantillons non remaniés) et les observations sur place du schiste argileux de Fort Union. Au barrage de Garrison, le plus grand barrage en terre roulée du monde, le schiste argileux de Fort Union forme la fondation des constructions et les schistes argileux provenant de l'excavation naturelle sont utilisés pour le massif roulé.

Introduction

Fort Union clay shales are predominantly lean and fat clays that have at one time been consolidated under loads estimated at between 80 and 100 tons per square foot. They underlay a region of 120,000 square miles in area which includes the site of Garrison Dam, at this time the largest rolled fill dam in the world which is being designed and constructed by the Corps of Engineers, Department of the Army. The Fort Union clay shales not only form the major portion of the foundation for heavy structures (intake, powerhouse and spillway) but the clay shales from the structural excavations are used in the rolled embankment. The size of the embankment (210 feet high, 11,500 feet long, containing 70 million cubic yards of material) and related structures make it important to have a thorough knowledge of the foundation material.

Geological Description

Garrison Dam and Reservoir are located in the western half of the state of North Dakota which lies in the northern part of the Great Plains physiographic province known as the Missouri Plateau.

Roughly dividing this region into glaciated (east) and unglaciated (west) portions is the Missouri River which flows in a southeasterly direction through the state in a series of east-west and north-south trending steps. Glacial history of the Missouri River is somewhat complex and continental glaciation has greatly influenced its present channel. There is evidence that the once eastward flowing streams with drainage into the north were truncated by the Missouri which was itself forced to take a southerly course after being blocked by ice on the north and east.

The present stream flows in a valley which is 2 to 4 miles wide and 200 to 400 feet deep. The valley itself (see Fig. 1) has been cut much deeper than the level at which the present river flows and in the past has also been filled with more alluvium than at present. This is evidenced by borings in the present flood plain which penetrate from 100 to 200 feet of alluvium and till before encountering bedrock and by terrace remnants which may be seen at various levels above the river throughout the valley.

The Fort Union group makes up the bedrock in a greater portion of the river valley within North Dakota. The dam site and probably the entire reservoir area lie in an upper portion of the group known as the Tongue River formation. This group is of early Tertiary (Paleocene) Age, and except for the lignite beds, sands, and an occasional thin strata of cemented limestone and sandstone, may be termed an immature (clay) shale. The clay shales can be classified and tested by procedures ordinarily applied to soils. Little cementing material is present, but the formation has been consolidated by super-imposed

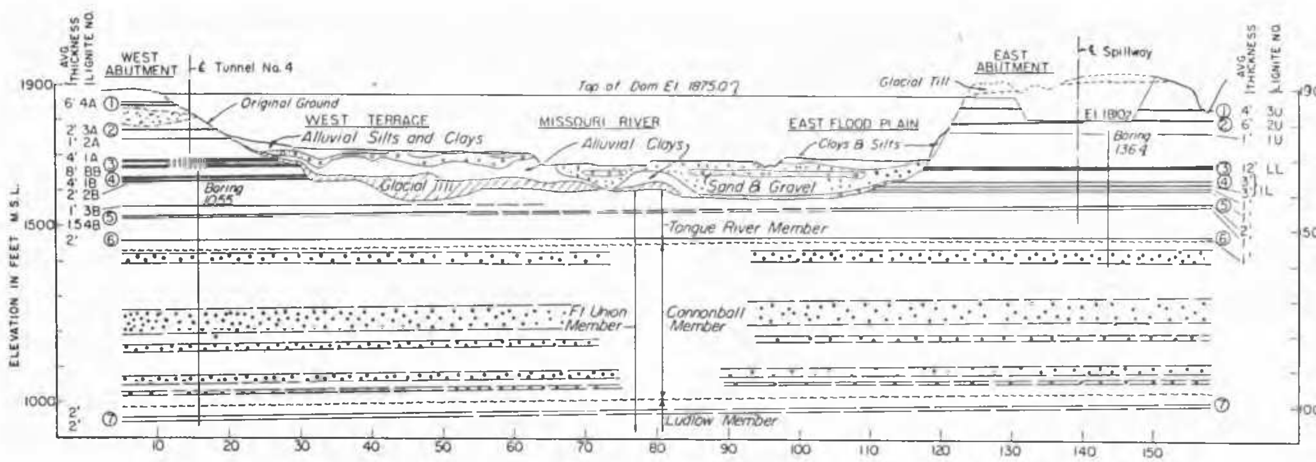

Fig. 1 Profile Centerline Dam. Looking Upstream
Coupe des lignes de centre du barrage. Direction amont

loads of similar material up to 1,500 feet in thickness. Repeated consolidation may have been brought about by at least two ice sheets which probably covered the dam site area in early Pleistocene times and terminated 50 miles more or less west of the river. Gradation of the sediments which make up the Fort Union varies from fine sand to fat clay with lean clays predominating. Horizons of an individual material are essentially flat lying, often cross-bedded, and vary in thickness from thin partings to over 15 feet, but the lateral extent of any one bed is limited. Prominent throughout the formation and especially at the dam site are beds of lignite which are jointed and cracked and are usually water bearing. The thicker beds may be traced for many miles and are used as correlative horizons. Slickensided fat clay layers are usually found adjacent to the lignite beds.

Soil Characteristics

Classification: Fort Union clay shales are predominately lean and fat clays with some sandy clays and clayey sands. The results of 175 Atterberg liquid and Plastic limit tests are shown on Fig. 2. All tests fall in the shaded zone above the *A* line. In consistency they are hard and vary in color from light brown, buff and grey in the weathered zone to more sombre and darker colors in the unweathered zone. Dr. *Ralph E. Grim* of the Illinois State Geological Survey reports the results of a differential thermal analysis on a sample of fat clay as follows: quartz (10 to 15 percent); clay minerals, 85 to 90 percent illite, 10 to 15 percent montmorillonite; 0 percent calcite and 1 percent plus or minus organic matter.

Density and moisture content: In dry density, the Fort Union varies between 95 and 115 pounds per cubic foot, and its moisture content ranges from 16 to 24 percent.

Specific gravity: Specific gravity varies from 2.66 to 2.72.

Laboratory Tests

Shear tests: A summary of direct shear tests is shown on Fig. 3 for consolidated drained (slow) and consolidated undrained (consolidated quick) tests. In both types of direct shear tests the samples were consolidated under a load equal or greater than their present overburden pressures and then sheared. In the consolidated drained tests the horizontal load was increased in increments and permitted to drain fully for each increment. In the consolidated undrained, the samples were quickly sheared under constant strain. Extreme variations of clay shale found in the formation and in many of the individual samples accounted for the large spread in the test results. A cohesion of 0.7 ton per square foot and a coefficient

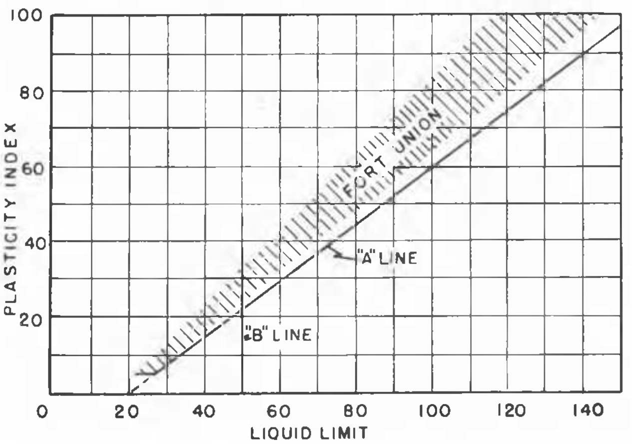

Fig. 2 Plasticity Chart
Diagramme de plasticité

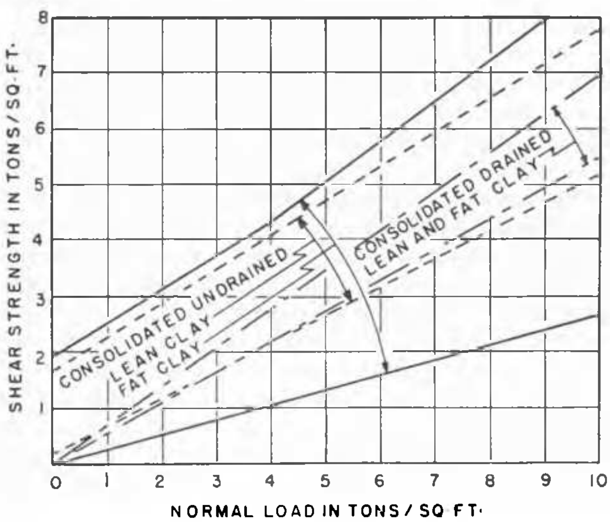

Fig. 3 Results of Direct Shear Tests
Résultats des essais de cisaillement direct

Fig. 4 Special Loading Device
Dispositif spécial de charge

of friction of tan. 20 degrees was used for the design of excavated slopes. Zero cohesion and a coefficient of friction of tan. 29 degrees was used for foundation design on unslickensided clays and tan. 25 degrees for slickensided clays. Pore pressures were calculated when using these latter values.

Consolidation: To check the preconsolidation load a special loading device was constructed as shown by the photograph, Fig. 4. Loads of 500 tons per square foot were obtained with this apparatus. A typical result is shown on Fig. 5. The results showed that the preconsolidation load could have been somewhere between 80 and 100 tons per square foot. Other tests on more conventional apparatus were performed up to 50 tons per square foot, and were cycled many times. These tests revealed that after the first cycle the compression index and swelling index did not vary appreciably. In its history the formation has been repeatedly loaded and unloaded. It is known from the elevation of buttes in the surrounding region that at least 1,500 feet of sediments once overlay the dam site and from surface evidence that it has been subjected to at least two glaciations. At the present time the formation is on a rebound branch of one of its many cycles. After studying the test results, it was decided to use a compression and swelling index of 0.018 for movement computations. The coefficient of consolidation when plotted against the average, pressure on semi-log paper is a straight line passing through 2×10^{-4} cm² per second at an average pressure of 4 tons per square foot and 9.5×10^{-4} cm² per second at 20 tons per square foot.

Permeability: The most permeable member of the Fort Union is the lignite which has a permeability coefficient varying

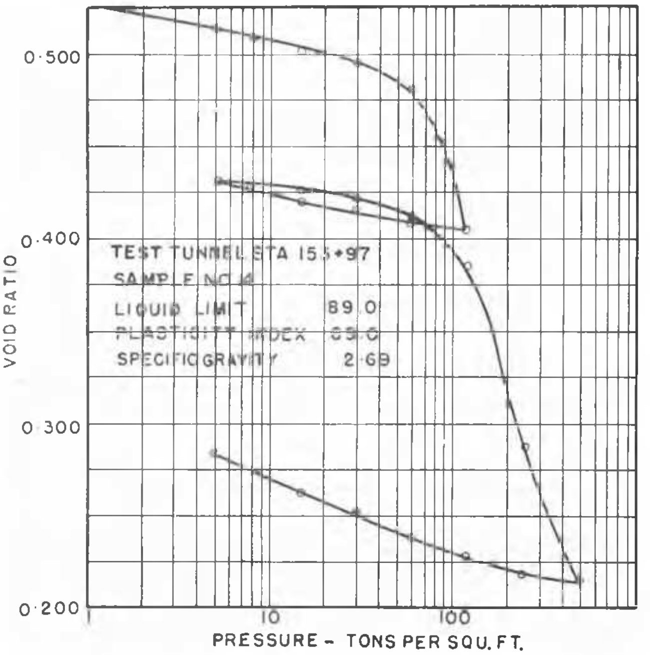

Fig. 5 Typical Result of a Loading Test
Résultat typique d'un essai de charge

from 800×10^{-4} to 200×10^{-4} cm per second. This coefficient was determined by pumping tests. The clay shales have permeability coefficients varying from $.01 \times 10^{-4}$ to $.0001 \times 10^{-4}$ cm per second.

Field Data

Slope curves: Studies of natural and excavated field slopes in Fort Union were conducted to check analytical studies before designing the permanent excavated slopes for the Garrison Project. A field slope chart, Fig. 6, summarizes the measured slopes. The solid line curves of Fig. 6 are the factors of safety from stability studies using a cohesion of 0.7 tons per square foot and coefficient of friction of tan. 20 degrees and circular arcs of failure. It is seen that the curve for factor of safety of 1.0 goes very close to the point representing the highest and

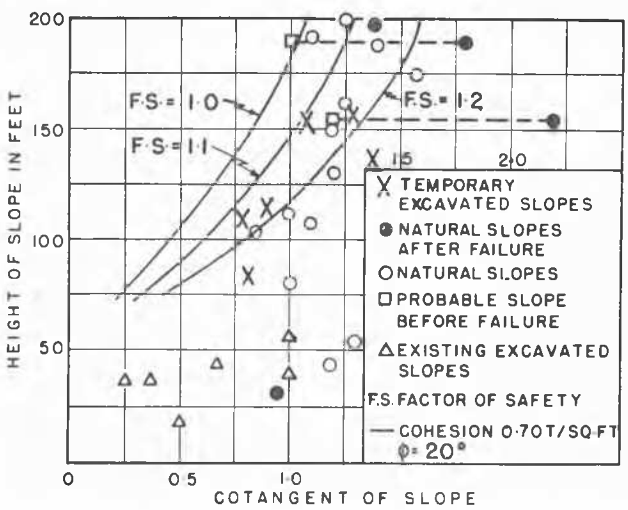

Fig. 6 Field Slope Chart
Diagramme des pentes des talus naturels

steepest slope as well as the point for one of the slopes that failed. This study of actual slopes in Fort Union is considered a check on the adopted shear strength values for large masses of Fort Union. In the final design of the permanent slopes for Garrison Project, the effects of lowering the ground water and the variation of reservoir pool were considered.

Elasticity: Fort Union clay shales are elastic and large rapid settlement and rebound occurs on loading and unloading. Both a time settlement due to consolidation and rapid settlement due to elasticity were calculated for all structures. By performing triaxial tests called constant stress ratio tests (the lateral load is kept at a constant ratio to the vertical load as the vertical load is increased) the modulus of deformation for a stress ratio of one-half was determined as 2,000 tons per square foot. Subsequent measured rebounds and settlements are approximately equal to the predicted value based on this constant.

Lateral Pressures: When saw cuts 3 inches wide and 7 feet deep were made at Elev. 1612 in the powerhouse area, the cuts closed in about 24 hours. This was attributed to yield caused by the release of tremendous lateral pressures that were induced by the overburden, which in the past ages was more than 1,500 feet higher than at present. The elevation of these cuts is about the minimum average elevation that the Missouri had ever cut in the Fort Union at the dam site as shown in Fig. 1. These high lateral pressures once may have existed in the formation at higher elevations, but the valley cut by the Missouri in the Fort Union allowed this higher material to yield laterally, thereby releasing this pressure. The floor of the valley prevented the lateral yield of layers at Elev. 1615 and lower.

Characteristics Based on Field Tests

Pressure Void Ratio Curves based on Field Data: The bluffs of the east abutment of Garrison Dam and the east flood plain differ in elevation by more than 200 feet and furnish a means of estimating the effect of unloading by erosion on the underlying strata of a large mass of material. A study was started in 1948 to estimate by field observations what effect this unloading caused and to see if it checked predictions based on laboratory data. In the bluff, Hole 972, surface elevation of 1924, was drilled to Elev. 1574 and in the east flood plain Hole 971, surface elevation 1693 was drilled to an elevation of 1574. A profile showing the relative positions of the borings is shown in Fig. 7*a*. In both borings below Elev. 1660 undisturbed soil samples were taken at every change of material. Liquid, plastic limits, moisture and density tests were performed on the samples and the results are shown in Fig. 7*b*. From the densities and moisture contents the void ratios were calculated for each

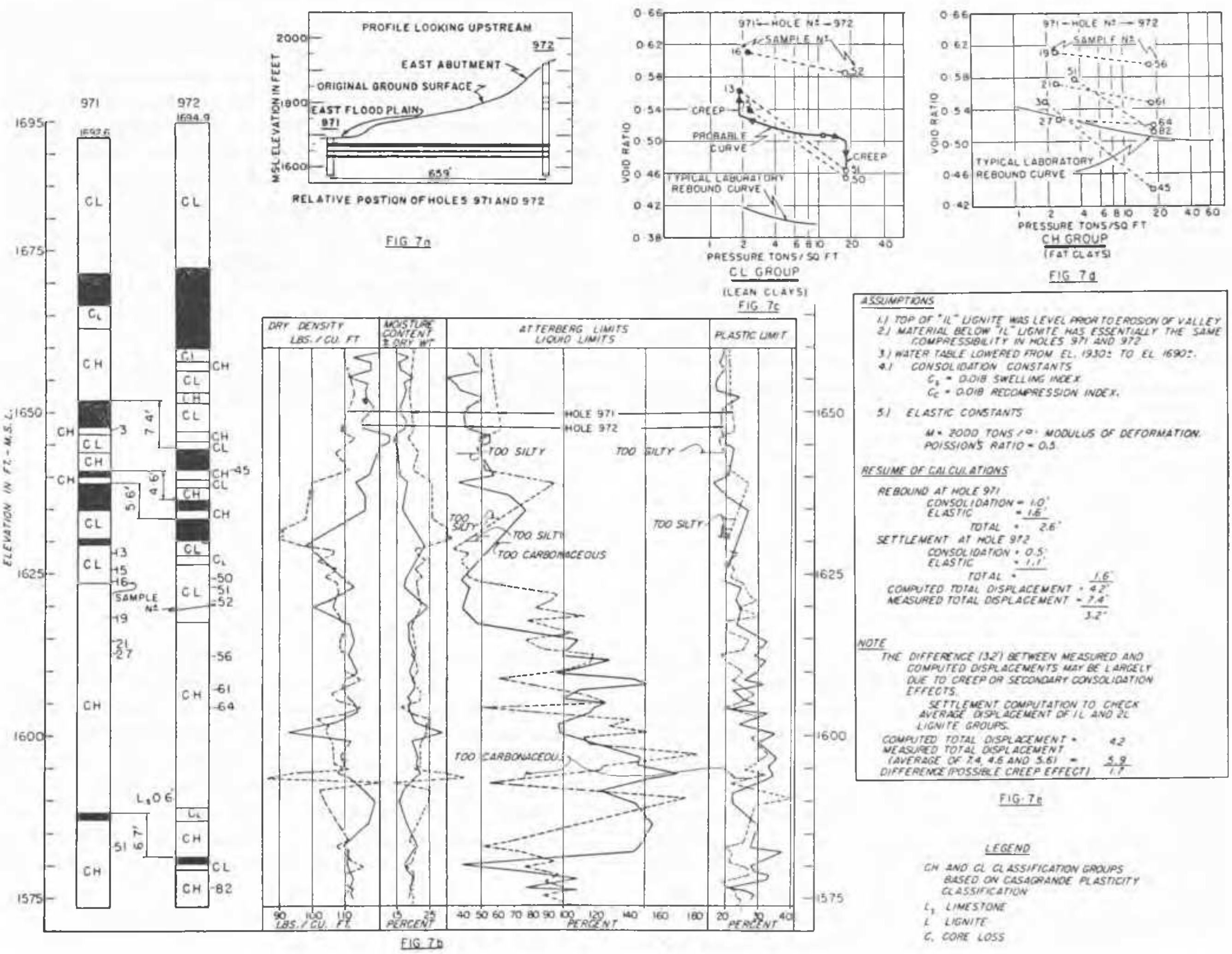

Fig. 7 Studies of the Effect of Unloading in the East Abutment
Etudes des résultats de décharge sur l'appui latéral est

sample. Pressure-void-ratio curves were drawn, as shown in Figs. 7*c* and *d*, for pairs of samples. The basis of selecting a pair of samples was that a sample from Hole 972 was a mate of a sample from Hole 971 if it had approximately the same liquid and plastic limits and their elevations varied similar to adjacent lignites. It was assumed that the existing pressure for any sample was equal to the present weight of material over the sample. The watertable was assumed at about Elev. 1690.

The average slope of the pressure-void-ratio curves derived from the above field study do not check the value of the expansion index of 0.018 adopted from laboratory tests. The average value from field tests was 0.05. It is believed that the reason for this difference is that the field data includes the long time secondary compression and swell (creep) which was not included in the laboratory data. Instead of a line being drawn directly from void ratio of a sample in Hole 972 to that of its mate in Hole 971, the soil could have followed the probable curve solid line from points 13 to 51 as shown in Fig. 7*c*. This would be the probable curve if the unloading had occurred relatively fast and then conditions remained the same over a long period of time. Similar conclusions have been arrived at by *A. Casagrande* (1949) in his studies of Saskatchewan Bearpaw Shale.

Check of characteristics using rebound of lignite beds: Logs of Holes 971 and 972, shown on Fig. 7*b*, show that the lignite beds of the flood plain (Hole 971) are a distance of 7.4 to 4.6 feet above similar beds in Hole 972. The lignite beds were probably level at the time they were laid down, and if the material below Holes 971 and 972 was uniformly compressible, the elevations of the lignite layers would furnish a measure of rebound caused by erosion of the valley. The rebound of 1L lignite bed was calculated, using the previously mentioned modulus of deformation of 2,000 tons per square foot and expansion and compression index of 0.018. No consideration was given to the secondary effects in the calculations. It is improbable that the formation in Holes 971 and 972 would have the same compressibility layer for layer, as the holes are 653 feet apart, but the depth of formation effecting the rebound, 600 feet, is so great that it was assumed that the average characteristics of the formation affected were the same.

For purposes of calculation the original surface of the ground and water table was assumed to be the top of Hole 972. As the water lowered and the river cut deeper and deeper into the formation, the lignite beds were exposed in the faces of the river bluffs, allowing the water in the beds to drain out. Ground water in the vicinity of the bluffs tended to seep vertically to the lignite beds, which act as horizontal drains. These two actions, the erosion of the valley which caused the formation below the valley to rebound and the lowering of the ground water table which caused settlement of the formation below the bluffs, combine to create a maximum difference in elevation of the 1L lignite between Holes 971 and 972.

Calculations summarized in Fig. 7*e* show that the rebound was 2.6 feet, 1.0 foot due to swelling and 1.6 feet due to elastic rebound, while the settlement caused by the lowering of the water table in the bluffs was 0.5 foot consolidation and 1.1 feet elastic compression. The sum of these effects is 4.2 feet. The actual measured difference in elevation of 1L lignite between Holes 971 and 972 is 7.4 feet and that for the 2L is 5.6 feet. The difference between the measured values and the calculated values could be due to the combined secondary compression (creep) of the soils represented by Hole 972 reducing in volume and those of Hole 971 increasing in volume.

Conclusions

At this time certain significant conclusions seem to stand out concerning the Fort Union clay shales. Of major importance is that the unloading of Fort Union clays even for long periods of time does not reduce its strength enough to endanger large structures; secondary compression and expansion can be of the same magnitude as consolidation; large horizontal forces exist in the clays below the elevations of eroded valleys in the formation; the *CL* clays usually swell more than the *CH* clays. (The cause of this is not understood at this time.)

A companion paper to this, "Rebound Gages Check Movement Analysis at Garrison Dam", compares the field data with the calculated rebound and settlement.

Reference

Casagrande, A. (1949): Notes on Swelling Characteristics of Clay-Shales. Harvard University, Pierce Hall, Cambridge, Mass., July, p. 12.