Earthquake Damage of Baihe Earth Dam and Liquefaction Characteristics of Sand and Gravel Materials

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Summary

The paper describes mainly the test results of the liquefaction of sand and gravel materials, explain the relationship of dry density and coefficient of permeability to the pore water pressure due to seismic action, and show that the main cause of flow slide of protective layer was the liquefaction of sand and gravel materials during earthquake.

I. Description of Earthquake Damage

Miyun reservoir is situated at the confluence of the Chaohe River and the Baihe River in the suburb of Beijing. The Baihe main dam is a sloping core earth dam with a maximum height of 66 m and a crest length of 960 m. It controls a catchment area of 15,700 km^2. The reservoir capacity is 4,300 million m^3. The sloping core of the earth dam is composed of medium to heavy silty loams. The designed dry density of the impervious core was 1.70 t/m^3. Both the downstream dam shell and the upstream protective layer were placed with sand and gravel materials. The designed dry densities of sand and gravel were 1.71 — 2.07 t/m^3, depending on the gravel contents of the materials. The actual dry densities had reached or exceeded the design standard. The dam foundation is an alluvium of sand and gravel, 44 m deep. A combination of concrete diaphram wall and grout curtain is used for controlling the underground seepage. Since the filling of the reservoir in 1960, the dam, which was once subjected to 93% of the designed water head, has been in good performance.

During the Tangshan earthquake on 28th July 1976, the seismic intensity at the dam site was 6°. A large slide occurred at the upstream protective layer of sand and gravel of the Baihe Dam. It covered a wide area of about 60,000 m^2, with a slide length of about 900 m, and a slide mass of about 150,000 m^3. At the moment of flow slide, the reservoir water level was at El. 138.4 m, while the slide mass was entirely located below El. 140 m. Almost all of the damaged portion were within the protective layer below the water surface; and only a localized damage was in the sloping core. The slid soils deposited over a long distance, having a greater part at a distance more than 40 m from the upstream dam toe and a small part at 100 m away. The soil particles of the slid mass became smaller and smaller with increasing distance away from the upstream toe. Cobbles and coarse gravels deposited at the upper part of the dam slope, while the fine materials deposited beyond the toe of upstream slope.

Just after the earthquake, measurements of the settlement and displacement of the earth dam were made. As compared with those before the earthquake, the maximum settlement was 59 mm and the maximum horizontal displacement was 28 mm towards downstream. No other earthquake damages such as cracks, abnormality of seepage, etc. were found except the flow slide of upstream protective layer.

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According to the seismograms of this strong earthquake, the duration of the earthquake was 114 sec. The maximum acceleration, the period, the duration and other characteristics are listed in Table 1 and Table 2. It can be seen from the tables that the features of this earthquake were long duration, great vertical component of acceleration, and large fraction of long-period pulses. The number of strong pulses (corresponding to 65% of maximum acceleration) exceeded 60, much more greater than statistical number of strong pulses (30 pulses) for other earthquakes of magnitude M=8. All these factors were important for worsening the flow slide of the upstream protective layer.

Table 1. Acceleration and Period of the Earthquake on 28th July at Baihe Dam

Observation point	Location	Direction	Maximum acceleration	Period of major pulses (sec)
a	Dam crest	Parallel to dam axis	160	0.57
a	Dam crest	Normal to dam axis	128	0.60
a	Dam crest	Vertical	66	0.25, 0.11 0.2-0.4
b	Downstream dam toe	Parallel to dam axis	39	0.2, 0.1-0.3, 0.45-0.70
b	Downstream dam toe	Normal to dam axis	53	0.2, 0.11 0.4-0.8
b	Downstream dam toe	Vertical	50	0.13, 0.25

Table 2. Time duration of the earthquake on 28th July at Baihe Dam

Observation point	Direction	t (sec) $(>\frac{2}{3}a_{max})$ *	t (sec) $(>\frac{1}{2}a_{max})$ *	t (sec) $(>\frac{1}{e}a_{max})$ *
a	Parallel to dam axis	13.7	23.1	35.0
a	Normal to dam axis	16.4	23.0	31.0
a	Vertical			
b	Parallel to dam axis	0.1	16.7	20.6
b	Normal to dam axis			
b	Vertical	4.4	30.6	40.0

* e — base of natural logarithm
a — seismis acceleration

A cylindrical container of diameter 40 cm was used in the tests, which were performed on a shaking table. The vibrating acceleration was 0.2 g (amplitude: 36 mm, frequency: 100 cycles per min.). Specimens were prepared according to the designed dry density. The degree of liquefaction can be calculated by the following equation:

$$K_t = \frac{U_t}{(\bar{\sigma}_1)_0} \times 100\%$$

where K_t — degree of liquefaction, %;

U_t — pore water pressure due to vibration at time t. kg/cm^2;

$(\bar{\sigma}_1)_0$ — initial effective vertical pressure at the point of measurement, kg/cm^2.

II. Liquefaction Characteristics of Sand and Gravel Materials

It can be noticed from the grain size distribution curves, as shown in Fig. 1 that the sand and gravel materials comprising the protection layer of Baihe earth dam have an average gravel content of about 60%, being discontinuous in size distribution and lacking the intermediate particles. The fine materials (grain size less than 5 mm) from the sand and gravel materials contain greater amount of fine grains, on an average about 76% of medium to fine sands. The gravel content of the testing material is about 57.7%. Some knowledge of liquefaction phenomena of sand and gravel materials is derived from the present investigation.

1. Relationship between gravel content of sand and gravel materials and their degree of liquefaction

In the earthquake resistant design, much attention has been given to the liquefaction of medium to fine sand. Inadequate attention, however, was given to the liquefaction problems

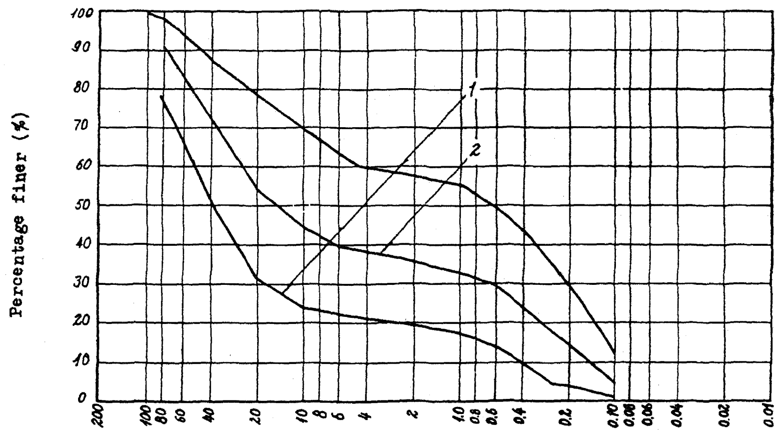

Fig.1 Gradation curves for the protection layer of Baihe earth dam

1 — Range of gradation curves for sand and gravel

2 — Average gradation curve for sand and gravel

of sand and gravel materials in the past. The present experimental study shows that the sand and gravel materials can also subject to liquefaction, and the degree of liquefaction depends upon the gravel content of the materials, but does not simply decrease with increasing gravel content. Fig. 2 illustrates that the degree of liquefaction is 74% for fine materials comprising only particles less than 5 mm, and increases to 90.5% for sand and gravel materials with a

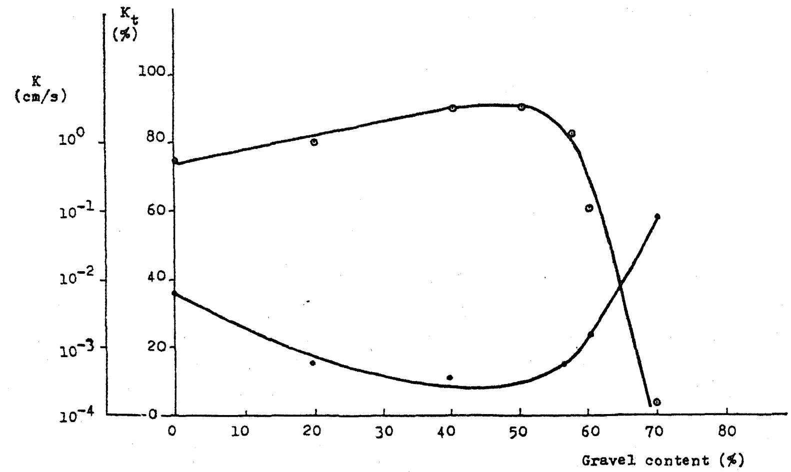

Fig.2 Coefficient of permeability versus degree of liquefaction for soil materials containing different amount of gravels

• -Pore water pressure • -Coefficient of permeability

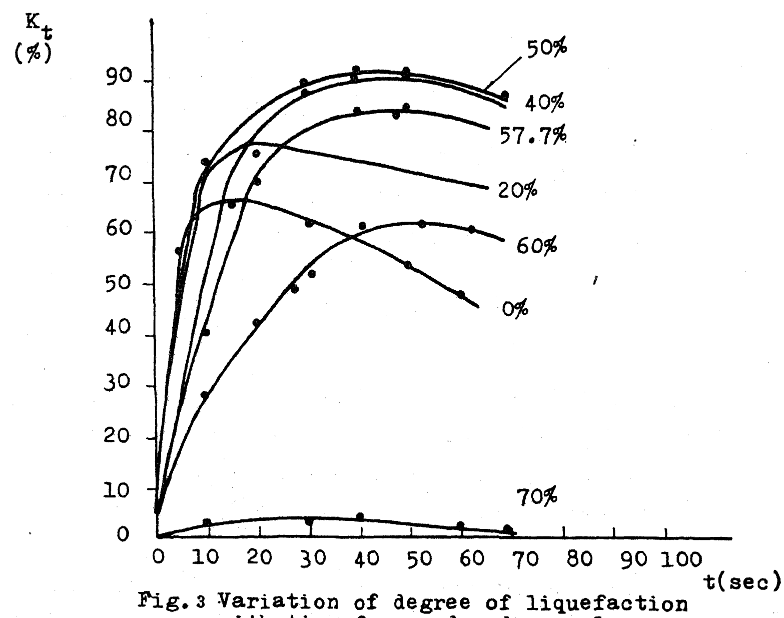

Fig. 3 Variation of degree of liquefaction with time for sand and gravel materials containing different amount of gravels

gravel content of 50% and then decreases progressively down to 40% for sand and gravel materials with a gravel content of 70%. The variation of the degree of liquefaction for sand and gravel materials with varying gravel contents is shown in Fig. 3 from which it can be seen that the time required for reaching the maximum degree of liquefaction is shorter for smaller gravel content, and increases with the increase of gravel content. For example, when the gravel content is less than 20%, the degree of liquefaction attains the maximum value within 15 — 20 sec, and when vibration continues or ceases the induced pore water pressure decreases quickly. When the gravel content is greater than 40 — 50%, the degree of liquefaction varies rather slowly, and attains the maximum value in 40 sec — 1 min. If the vibration continues further or ceases, the induced pore water pressure also decreases slowly. Thus it can be concluded that all the sand and gravel materials with gravel content less than 70% have the potential of liquefaction, but the time needed for reaching the maximum degree of liquefaction will be longer for higher gravel content.

2. Relationship between dry density of sand and gravel materials and their degree of liquefaction

It was generally considered that the degree of liquefaction decreases as the initial dry density of soil materials increases. From the present tests it has been found that the degree of liquefaction, either for sand and gravel materials or for fine materials only, does not simply decrease with the increase of initial dry density, but also has a maximum value like its relationship to gravel content. From the test results shown in Fig. 4, it can be seen that in the case of fine materials tested at a vibrating acceleration of 0.2 g, the degree of liquefaction increases with the increase of initial dry density when the initial dry density is less than 1.65 g/cm^3, and vice versa when the dry density is greater than 1.65 g/cm^3 (corresponding to a relative density of 0.45). In other words, at the initial dry density of 1.65 g/cm^3 the degree of liquefaction reaches its maximum value, i.e. the pore water pressure due to vibration also reaches its maximum. For the same material but tested at an acceleration of 0.1 g, the degree of liquefaction reaches its maximum at the dry density of about 1.66 g/cm^3. We shall herein temporarily define this dry density as the "dry density at maximum degree of liquefaction". From Fig. 4 it is also noticed that the sand and gravel materials will have different "dry density at maximum degree of liquefaction" for different gravel contents, e.g. 1.97 g/cm^3 for 50% of gravel content.

Furthermore, for the above-mentioned test material with 50% of gravel content the reduced dry density of the fine fraction is also calculated and plotted on the left side of fig. 4. It can be noticed that, for similar vibrating acceleration 0.2 g, the degree of liquefaction of the fine fraction of sand and gravel material is higher than that of the fine materials when the dry density is less than 1.62 g/cm^3, but the case is reversed when the dry density is greater than 1.62 g/cm^3. The dry density of 1.62 g/cm^3 of the fine fraction (in the sand and gravel materials with a gravel content of 50%) is equivalent to a dry density of 2.01 g/cm^3 for the whole materials. This value was reached during construction compaction. Thus it can be concluded that if the large-scale vibrating triaxial equipment is unavailable, the results of dynamic shear test made on fine fraction (<5 mm) can be applied to sand and gravel fill with good compaction quality.

From Fig. 4, it can also be noticed that if the requirement of no development of pore water pressure due to vibration is used as the criterion for determining the placement dry density, when the acceleration is 0.2 g, the placement dry density of sand and gravel materials with 50% gravel content should be 2.14 g/cm^3, which corresponds to a relative density of 0.75. However, the compaction dry density of the sand and gravel materials during construction of the protective layer of Baihe earth dam is equivalent to a relative density just less than 0.6, which is in the range of medium dense state. In the present test, the relative density was performed

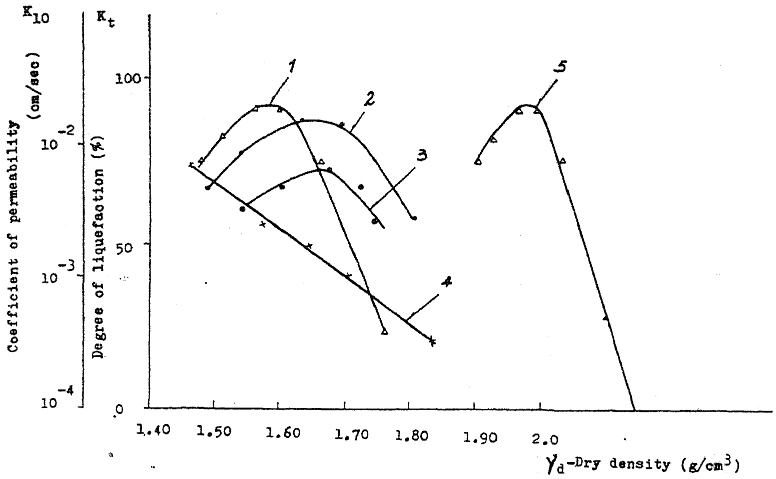

Fig.4 Degree of liquefaction versus dry density

1 — Fine materials from sand and gravel with 50% of gravel

2 — Fine materials (0.2 g)

3 — Fine materials (0.1 g)

4 — Coefficient of permeability for materials

5 — Sand and gravel containing 50% of gravel (0.2 g)

on the shaking table. According to test data obtained in this way, the relative density of the sand and gravel materials corresponding to the placement standard is only 0.32, which lies in the range of loose state. Both the above-mentioned two results of relative density are much smaller than the required relative density based on no development of pore water pressure under the action of vibration. This may be one of the most important causes of the slope failure occurred in Baihe earth dam. The fact that there is great difference in the results obtained from these two test procedures indicates that it is still necessary to further study the test procedures for determining the relative density of sand and gravel materials.

3. Relationship between degree of liquefaction and coefficient of permeability

In order to explore the causes of the appearance of peak values on the curves relating the degree of liquefaction to gravel content and to dry density, the coefficients of permeability for sand and gravel materials with different gravel contents and for fine materials with different dry densities are determined and drawn in Fig. 2 and Fig. 4 respectively.

Fig. 2 shows the variation of coefficient of permeability of sand and gravel materials with the gravel content. The coefficient of permeability decreases with increasing gravel content when the gravel content is less than 45%. It reaches the minimum value when the gravel content is about 45%.. This is attributed to the fact that the coefficient of permeability depends on the amount of seepage channels in the fine fraction (<5 mm), when the coarse grains, before acting as skeleton, are surrounded by the fine fractions. In the case of a certain dry density the area of seepage channels in the fine material decreases because the coarse grains themselves are impervious. This is the decrease of coefficient of permeability with initial increase of gravel content. When the gravel content further increases, direct contacts are developed between coarse grains, and the fine materials filling the pore space of coarse grains may not be compacted effectively, or even cannot fill the whole pore space. Therefore, the coefficient of permeability will increase. It reaches its minimum value when the coarse grains just form a skeleton and when the fine materials fill up the whole pore space of the skeleton to be effectively compacted. Fig. 2 illustrates that the tendency of development for the curve of degree of liquefaction versus gravel content is just opposite to that for the curve of degree of liquefaction versus coefficient of permeability, but the gravel content is more or less the same at maximum degree of liquefaction and at minimum coefficient of permeability. For the sand and gravel materials used in the tests, the gravel content at maximum degree of liquefaction is about 45%, and the corresponding coefficient of permeability is 3×10^{-4} cm/sec.

The relationship between the coefficient of permeability and dry density of fine material, illustrated in Fig. 4, shows that the coefficient of permeability decreases as the initial dry density of the specimen increases. Under the same drainage condition, the degrees of liquefaction for sand and gravel materials and for fine materials are mainly dependent upon two factors, i.e. the tendency of densification during vibration and the coefficient of permeability. When the dry density of the test specimen is less than the "dry density at maximum degree of liquefaction", the specimen is in loose state or in medium to loose state. Both states have quite similar tendency to be densified a great deal and have little difference in the induced pore water pressure. Therefore, a reduction of the coefficient of permeability leads to a reduction of the rate of dissipation of pore water pressure and an increase in the degree of liquefaction. When the dry density becomes greater than the "dry density at maximum degree of liquefaction", the specimen is in medium to dense state or in dense state, and its tendency of densification greatly reduces. Thus, the induced pore water pressure will also decrease considerably. This is the main factor controlling the degree of liquefaction. The effect on the rate of dissipation due to further decrease in coefficient of permeability is insignificant in these cases. As a result, the peak value also appears in the relationship between dry density and degree of liquefaction.

It is necessary to indicate that the interrelationships among the degree of liquefaction, gravel content, dry density and coefficient of permeability are obtained from the tests in cylindrical container in which the specimens are laterally confined and drainage is permitted only in upward direction. Both the stress and the drainage conditions cannot be controlled. The result obtained is of great significance to the study of liquefaction of sand and gravel materials, but it is still qualitative. The peak value of degree of liquefaction and the corresponding gravel content and dry density of fine fraction will vary with the boundary condition and the material properties of each particular engineering project.

III. Conclusion

The testing results show that the sand and gravel materials with gravel content less than 70% are liable to liquefaction. Their degree of liquefaction is closely related to gravel content, dry density and coefficient of permeability.

The main factors contributing to the flow failure of upstream protective layer of Baihe earth dam due to liquefaction are as follows:

(1) The sand and gravel materials with an average gravel content of 60% are a kind of materials susceptible to liquefaction.

(2) The placement dry density corresponds to a relative density less than 0.6, which is still low.

(3) The drainage condition is poor because of no drainage layer and because of the pointing of rubble revetment with cement mortar.

(4) The long duration and large number of strong pulses during Tangshan earthquake.

It is worthy of noticing that although the relative density is an important index for the control of compaction quality, different testing procedures will give quite different results and, consequently, further study in this aspect is needed.