DEVELOPMENT OF GEOTECHNICAL ENGINEERING IN CIVIL WORKS AND GEO-ENVIRONMENT

Editor
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Perkembangan ilmu Geoteknik yang semakin pesat dan pemberlakuan Undang-Undang Jasa Konstruksi No. 18 tahun 1999 mendorong tumbuhnya profesionalisme di dalam dunia konstruksi. Dunia pendidikan tinggi, melalui Direktorat Jenderal Pendidikan Tinggi, juga sedang giat meningkatkan hubungan dengan dunia profesional sehingga pengembangan pendidikan dan profesi mempunyai keterkaitan yang semakin jelas dan kuat. Geoteknik sebagai bidang ilmu yang berkait dengan teknik tanah, diharapkan lebih profesional dalam melakukan perencanaan dan pelaksanaan konstruksi termasuk memperhitungkan kemungkinan resiko kegagalan konstruksi.

Berdasarkan konstelasi dunia pendidikan dan dunia konstruksi tersebut, Himpunan Ahli Teknik Tanah Indonesia (HATTI) sebagai asosiasi tempat bernaungnya para praktisi dan ahli geoteknik, berupaya meningkatkan kompetensi para anggotanya maupun kalangan lain yang berminat dalam bidang Geoteknik. Sebagai salah satu kegiatan rutin HATTI, maka Pertemuan Ilmiah Tahunan-XIV ini mengangkat tema "Perkembangan Geoteknik dalam Pelaksanaan Konstruksi Sipil yang Berwawasan Lingkungan". Acara ini diharapkan menjadi ajang komunikasi dan tukar menukar informasi bagi para professional yang bergerak dalam bidang konstruksi geoteknik, khususnya untuk menyoroti secara cermat masalah-masalah geoteknik, termasuk potensi dan resiko yang akan dihadapi serta upaya dalam mengatasinya. Prosiding ini sangat berguna sebagai referensi sekaligus informasi bagi para ahli geoteknik guna memecahkan permasalahan yang menyangkut tanah di Indonesia.

Atas kerjasama yang baik dan bantuan dari semua pihak dalam menyuskeskan Pertemuan Ilmiah Tahunan-XIV, panitia mengucapkan terima kasih.

Yogyakarta, 10 Februari 2011

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Geotechnical Analysis of Earth Dam Failure

Teuku Faisal Fathani

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ABSTRACT: Situ Gintung dam failure on 27 March 2009 has caused more than 100 casualties from a tsunami caused by more than 10 m/s flow velocity resulted from the embankment failure in only less than 2 hours. Prior to the dam failure, a relatively high intensity of rainfall (more than 70 mm/hrs) occurred at the catchment area. Besides, the embankment structural condition was far from fair. These were indicated by apparent physical conditions such as too narrow spillway, insufficient width of spillway crest, imperfect interface between spillway structure and soil embankment, utilization of downstream embankment for housing, road, etc. These, of course contributed the Situ Gintung dam failure phenomenon which needs to be studied thoroughly. The geotechnical analysis indicates that interaction between the dynamic of reservoir water level and the cutting slope of earth dam plays a significant role in the occurrence of dam failure. The appurtenances of Situ Gintung and the cutting slope due to the houses construction were evaluated to understand the historical aim of the dam development. A two-dimensional stress-deformation analysis has been performed to figure out the distribution of relative shear stress and plastic points on the dam embankment at the time of failure. The safety factor decreases from 1.43 at the un-interfered embankment to 1.27 due to the cutting slope and the increase of reservoir water level.

Keywords: earth fill dam; dynamic of water elevation; interfered embankment; safety factor against failure

1. INTRODUCTION

Situ Gintung, located in Tangerang Regency, Banten Province, was built in 1933 for irrigation purpose. Situ Gintung was a small natural lake, where the water mass was trapped in a basin at a ridge. The dam embankment is built at the tributary of Pesanggrahan River by constructing earth fill embankment at the north mound to increase the reservoir capacity. Before the dam failure, Situ Gintung served as a catchment dam and tourism area. The intakes at both embankment edges were not functioned, as the farm areas had changed into settlement areas. Situ Gintung area had shrunken from 31.00 ha to 22.79 ha. The reservoir capacity according to the Ministry of Public Works (2009) was 810.000 m$^3$ at the elevation of +98.00 m. The maximum height of the earth fill embankment is 10 m, with the length of 180 m.

At the deepest part of the basin of Pesanggrahan River tributary, a masonry structure for spillway of 11.20 m wide was built. In 2004, two pillars were constructed on the spillway crest to support a small bridge, hence the spillway width decreased to 10 m. The width of steep channel decreased due to the settlement, and the stilling basin was constructed at the downstream. Excessive discharge flows through the tributary of Pesanggrahan River.

After a heavy rain on the previous day, on 27 March 2009 at 4.30 AM, the embankment and spillway collapsed, causing a flash flood in the downstream area resulting in over 100 deaths. The collapsed embankment was about 50 m wide. Prior to the dam failure, Ministry of Public Works (2009) reported that the reservoir water level was about +99.00 m or 1.00 m below the embankment crest. Legono et al. (2009) revealed that before the collapse, the Situ Gintung water level reached +98.75 m or 1.25 m below the embankment crest.

This research aimed at analyzing the structural integrity of an earth dam at Situ Gintung from the geotechnical aspect by conducting data compilation from fact-findings, geotechnical investigation, and hydrology-hydraulics analysis. Further, stability analysis was analyzed by considering the dynamic of reservoir water elevation, slope disturbance due to housing, and the existence of external load.
2. EMBANKMENT STRUCTURAL CONDITION

Based on the visual observation and secondary data compilation, several phenomena related to spillway and embankment condition were found. The remaining embankment consists of stiff silty clay with high-plasticity. The soil can be categorized as laterite soil from volcanic material decayed. The soil composing embankment body is assumed in a good condition, particularly the right side embankment with very steep sliding surface (Fig. 1). The downstream slope of the right embankment is mostly open land, yard, and bushes. From the observation, there was no crack or piping on the existing embankment body.

The existence of soft soil layer with the thickness of 50 cm at the base of right embankment may also affect the failure phenomenon considerably (Fig. 2). The spread area of this layer could not be clearly observed. This soft soil has low shear strength, high plasticity and is strongly affected by the fluctuation of pore water pressure. The damages of embankment structure affect the stability of the slope, particularly when the sliding surface passes through this soft soil.

In the downstream slope of left embankment, cutting slope for permanent houses construction was found. From the information obtained from the local community, most houses made dug and drilled wells for their water supply. The slope cut, additional external load, and soil excavation for wells, house foundation, septic tank, etc. would reduce the embankment stability significantly. In the center of the failed embankment, a hanging electricity cable was seen, indicating that the embankment body had experienced a disturbance from cable installation of 1 meter deep. The left embankment condition after the collapse is shown in Fig. 3, where the houses were built by cutting the downstream slope up to the embankment crest. At the outcrop in the center part of the failed left embankment and at the lower downstream of the left embankment, the seepage through rock sand layer was found.

At the failed embankment, small-scaled local collapses occurred continuously. In the rainy season, secondary landslide can be occurred, which may form a smaller natural dam, composed of loose material. If this is not adequately controlled, it may cause a flash flood in a smaller scale.

The spillway is situated in the center of the collapsed embankment. Fig. 4 shows the condition of the left part of the spillway and embankment before the failure. At the downslope of embankment wall and the interface of embankment-spillway, the damage due to water erosion can be seen. This condition can reduce the stability of the spillway and weaken the interface of embankment-spillway. Another observed phenomenon was surface failure in slope protection at the toe of upstream slope. A more detail information on the spillway structure has not been found so far.

From the observation, there was no overtopping before the embankment failure. The structural condition of the embankment body (particularly the right embankment) is in fair condition. The toe of upstream slope was covered with soft material from reservoir sedimentation. Slope damages were also found in the upstream of left embankment and in the existing embankment of the east side of Situ Gintung.
To perform a stability analysis against dam failure, geometric profile and its corresponding soil stratification is needed. As previously explained, the right and the left embankment have a different geometric profile due to disturbance of cutting slope and additional external load in the left embankment. Based on the geometric profile and the result of geotechnical investigation, a geometrical section and soil layering in the right and left embankment body is determined as shown in Fig. 5.

The results of laboratory test show that the soil is dominated by high plasticity clay or silt (CH-MH) and is not easily eroded (non-dispersive soil). The right embankment body, near the spillway, has the cohesion value of 12 – 32 kN/m² and internal friction angle of 19º – 29.5º. In the center of the collapsed embankment, the cohesion is 3 – 15 kN/m² and internal friction angle is 25.4º – 37.5º. The soft soil layer at the toe of upstream slope on the right embankment has a high water content of 78.69% which is close to its liquid limit (81.35%), with the plasticity index of 41.07%. Soil physical characteristic has the specific gravity of 2.68, unit volume weight of 1.35 gr/cm³, and coefficient of permeability of 5.13 x 10⁻⁷ cm/s. Undrained cohesion value from Unconfined Compression Test is fairly low (0.07 kg/cm²). From Direct Shear Test, the cohesion is 0.097 kg/cm² and internal friction angle is nearly zero. Since the spread area of soft clay layer cannot be observed clearly in the peel embankment, the soil layering in the analysis refers to the result of core drill and laboratory test.
4. STABILITY ANALYSIS AGAINST FAILURE

In order to determine the stability condition of the embankment near the spillway of Situ Gintung at the time of the failure, a geotechnical modeling is performed. Analysis of embankment structural stability uses stress-deformation analysis by Finite Element Method (FEM), stability analysis by Limit Equilibrium Method (LEM), and seepage analysis by modeling hydraulic gradient fluctuation to analyze the possibility of piping occurrence.

By considering the geotechnical condition, the result of hydrology and hydraulics analysis in the form of rainfall-runoff characteristics at Pesanggrahan River and its tributary, and dam break phenomenon (Rahardjo et al., 2009; Legono et al., 2010), the geotechnical modeling was performed on four geometric cross sections, as described below.

(i) **Section A**: left embankment of the spillway, with the assumption that there is no disturbance on the embankment slope. The result will be compared to the slope with disturbance on downstream slope.

(ii) **Section B**: left part of the existing embankment, which experienced disturbance on the downstream slope due to the construction of one-story houses.

(iii) **Section C**: left embankment of the collapsed spillway, with cutting in the downstream slope and two-story houses constructed at the upper slope.

(iv) **Section D**: right embankment, which relatively did not experience any disturbance and most of the downstream area is open land or yard.

In the stress-deformation analysis by Plaxis, a plane strain idealization form was applied. In every observed geometric section, the impact of jogging track constructed at the embankment crest was also simulated. Applied distributed load to the model in the form of pedestrian load is 0.05 ton/m² and vehicle load is 0.8 ton/m². From the result of analysis, the most critical condition occurred at the left embankment near the collapsed spillway with cutting slope and two-story building load. The critical condition occurred during the highest water level of +98.75 m. Total deformation of the left embankment reached 82.3×10⁻³ m and the safety factor decreased from 1.63 in undisturbed condition (Cross-section A), to 1.43 (Cross section B). The safety factor dropped considerably to 1.27 due to extreme slope cut with two-story building load (Cross-section C).

The shear stress is distributed in the core of embankment body, the face of upstream downslope, and in the downstream cutting slope (Fig. 6). Plastic point distribution in Fig. 7 gave a distinctive illustration that potential for structural progressive failure is distributed to several critical points i.e. upstream downslope of the embankment, the core of embankment crest, downstream cutting slope and along the toe of downstream slope. Embankment instability process was initiated by progressive failure occurred on those critical points.

![Fig. 6 Relative shear stress distribution in the left embankment (Cross-section C) with the deformation of 82.3×10⁻³ m and SF = 1.27.](image)

The downstream slope of right embankment experienced the most critical condition at the highest water level of +98.75 m. Total deformation reached 88.1×10⁻³ m and the safety factor is 1.89. The shear stress is distributed in the core of embankment body, the toe of upstream and downstream slope. The potential of the structural failure is distributed to several critical points: at the toe of upstream slope, the core of embankment crest, and below the toe of downstream slope.

Fig. 8 shows the increase of deformation and decrease of safety factors against dam failure at the increase of reservoir water level at various sections. It can be found that in every cross-section, the critical condition occurred when the water elevation in Situ Gintung reached the highest level of +98.75 m. Safety factor is believed to be smaller if the embankment structural defect due to the disturbance is considered in the analysis. The increase of reservoir water level from +96.00 to +98.75 m caused an increase of total deformation. Additional external load due to the existence of jogging track caused a slight decrease in the total deformation (less than 1 mm). The construction of jogging track had reduced the safety factor of less than 0.05 for every cross section. Consequently, it can be concluded that the jogging track construction did not have any significant impact to the embankment stability as previously alleged.
The LEM stability analysis of upstream and downstream slope was conducted by using Morgenstern-Price Method. The most critical condition in the downstream slope is at the highest water elevation of +98.75 m. In the downstream of Cross-section C, the safety factor decreased from 3.00 (water elevation of +96.00 m) to 2.41 (water elevation of +98.75 m). In general, the increase in water elevation caused a decrease in the safety factor of downstream slope while the safety factor of the upstream slope did not experience any significant change due to the limitation in modeling the submerged landslides. A more accurate method for submerged slope stability analysis with arbitrary shape of sliding surface is by using dynamic programming combined with Janbu Method (Fathani, 2004; Fathani and Nakamura, 2005).

Seepage analysis showed that the exit gradient of Cross-section A is 0.208. The safety factor against piping is 4.80, higher than 4.00. Therefore, the piping would not occur in the embankment. In the same way, the exit gradient of Cross-section B, C and D are 0.238, 0.285, and 0.0915, respectively. The safety factor against piping on Cross-section B and D is higher than 4.00. Due to the extreme disturbance on Cross-section C, the safety factor against piping reduced to 3.51, hence the piping might occur in this cross-section. Fig. 9 shows the seepage analysis on the left embankment (Cross-section C).

Fig. 9 Seepage analysis on the left embankment (Cross-section C); exit gradient = 0.285; safety factor against piping = 3.51.

5. EARTH DAM FAILURE MECHANISM

5.1. Embankment Stability

From the result of stress-deformation analysis by FEM, downstream slope on the left and right embankment has lower stability than the upstream slope. The higher water elevation, the lower safety factor against failure is. Safety factor reached the lowest value when reservoir water level reached its highest level of +98.75 m. The right embankment is in fair condition with safety factor of more than 1.80. From the field observation, high plasticity soft clay was horizontally distributed at the base of the right embankment. This layer has low shear strength and is highly affected by saturation process.

The left embankment condition experienced a disturbance in the form of slope cutting and additional external load that almost reached the embankment crest. This can reduce the resisting forces and at the same time, increase the driving forces. The change in the function of an earth dam slope into settlement area may cause defects to the embankment structure. Accordingly, embankment structure defects can cause an increase in discontinuity plane which may develop into critical sliding surface with low safety factor. Due to defects in the left embankment, the actual safety factor is supposed to be lower than 1.27. However, in the analysis using FEM, defects in the embankment body was not considered.

The instability condition can also be observed from the relative shear stress distribution and plastic points from the beginning of progressive failure process until the occurrence of failure. The critical parts of the embankment are the toe of upstream slope, the core of the embankment crest, the upstream cutting slope and along the toe of downstream slope. Disturbance on the critical parts of the embankment can reduce the stability level and is one of the causes of embankment and spillway failure in Situ Gintung.

From the analysis and field observation, causative factors of embankment and spillway collapse can be
categorized from the factor giving the biggest contribution to the factor giving the smallest contribution to the embankment stability, i.e. (1) utilization of downstream embankment for housing; (2) too narrow spillway and insufficient width of spillway crest; (3) imperfect interface between spillway structure and soil embankment; and (4) Situ Gintung water level which reached its highest elevation of +98.75 m, reducing the safety factor.

5.2. Breaching Mechanism

Breaching mechanism is highly affected by water level fluctuation and its interaction with earth fills material that usually forms a seepage line in the embankment body. Yoshimatsu (1981) revealed that reservoir-induced landslide might occur due to the rising of water level or rapid drawdown. Fathani dan Nakamura (2005) had analyzed the mechanism and causes of 15 submerged landslides in 10 dam reservoirs in Japan occurring from 1980 to 2002. Most of submerged landslides in Japan are caused by rapid rising of water level due to high rainfall intensity with long duration. In Situ Gintung case, whether the breach was caused by rapid rising of water level is difficult to conclude since there was no Automatic Rainfall Recorder (ARR) and Automatic Water Level Recorder (AWLR) installed in Situ Gintung.

An earth dam failure process can happen through overtopping or breaching mechanism. In breaching mechanism, a part of embankment body material (particularly downstream slope) experienced instability due to soil strength reduction. This phenomenon can be observed from the result of laboratory test, showing a significant soil shear strength reduction (cohesion component) in saturated soil material. Significant reduction of shear strength will occur with the increase of hydraulic gradient and the occurrence of seepage and piping.

From the in-situ permeability test on the left and right side of the collapsed spillway, the permeability coefficient of the existing embankment is fairly impermeable, i.e. $10^{-6} - 10^{-5}$ cm/sec. Earth fill material of the existing embankment is mostly composed of clay fraction or high plasticity silt or clay (CH-MF), with fine content of 79.20% - 97.30%, and non-dispersive. The soil layer at the bottom of embankment is consolidated or cemented material having permeability coefficient of $10^{-5} - 10^{-4}$ cm/sec. Therefore, earth fill material and existing embankment foundation have a good stability against erosion.

Breaching is generally started with certain signs, for example leak or seepage in the downstream of embankment body, accompanied with turbid water. However, due to limited information, it is difficult to conclude whether piping occurred before the breach.

As previously explained, the earth fill material and foundation of the existing embankment have good stability against erosion as long as the embankment structure does not experience any defect. Considering the extreme slope cutting and additional load in the left embankment, it is possible that a piping had occurred in the area of the left side of spillway before the failure. This is supported further by the result of stress-deformation analysis where the distribution of plastic points is centered in the location of slope cutting, causing tensile stress. The discontinuity plane which might be initially eroded is at the location of slope cutting, at downstream slope toe, and the interface between spillway left-right wall and earth fill embankment. Water level fluctuation in Situ Gintung can increase the scouring process in the interface of spillway and embankment body from time to time. This phenomenon can eventually reduce the stability of embankment structure and spillway, causing total failure which is allegedly started from the spillway of left embankment.

6. CONCLUSIONS

Situ Gintung failure is caused by left embankment structural instability and breaching mechanism. The instability occurs due to cutting slope and additional external load reaching the embankment crest, which in turn will reduce the safety factor. Disturbance on earth dam will cause defects in the embankment structure, which may form the discontinuity plane having lower safety factor. The instability condition can be observed from relative shear stress distribution and plastic points at the time of progressive failure started until the failure. The critical parts of the embankment are the upstream slope, the core of embankment crest, downstream slope cutting (with tension crack) and along the toe of downstream slope.

Breaching mechanism can be observed by the significant soil shear strength reduction in the saturated soil material. An excessive shear strength reduction occurs as the hydraulic gradient increases, accompanied with seepage and piping. The earth fill material and the existing embankment foundation have a good stability against erosion as long as there is no defect in the embankment structure. Based on the observation on the disturbance occurring in the left embankment, a piping process in the left wall of the spillway might have occurred before the collapse. The discontinuity plane that was initially eroded is the interface between spillway left wall and earth fill embankment.

As a mitigation effort, it is necessary to conduct the monitoring of reservoir water level, dynamic of pore water pressure, crack condition, erosion and deformation of embankment structure by placing the appropriate instrument. The monitoring result will be the basis of reservoir operation and maintenance, to avoid embankment instability due to shear strength reduction.
and piping. A more comprehensive investigation should be performed in the embankment surrounding the dam. The spillway construction design should consider the interface with the existing embankment which is a weak point and the placement of the foundation that should be supported by strong soil layer. Aside from that, the strengthening of the existing embankment structure and slope protection must be designed to ensure the stability.

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