General report
Geotechnical problems of dikes (TC 201) and dams (TC 210)

Rapport général
Problèmes géotechniques dans les digues (TC 201) et barrages (TC 210)

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ABSTRACT: Among the papers submitted to the 18th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2013), 11 papers are catalogued in the field of dike and dam, with 4 paper on dike and 5 papers on dam. By reviewing the submitted papers and recent development in related field, the general report for the joint session of TC201 (dike) and TC210 (dam) of ISSMGE Conference (Paris 2013) was presented. Besides the brief comments on the submitted papers, the general report discussed some selected geotechnical issues of dikes and dams. For dikes, the discussion is mainly focus on overtopping flow erosion, internal seepage instability and bank collapse. For dams, some key technologies for building high rockfill dam were presented, which includ properties of construction materials, foundation treatment, dam deformation control and hydraulic fracture of earth core.

RÉSUMÉ : Parmi les articles présentés au 18^{e} Congrès International de Mécanique des Sols et de la Géotechnique (CIMSG 2013), 11 articles sont catalogués dans le domaine des digues et barrages, avec 4 articles sur les digues et 5 sur les barrages. En passant en revue les articles présentés ainsi que les développements récents dans le domaine, le rapport général de la session conjointe des TC201 (digues) et TC210 (barrages) du congrès de la SIMSG (Paris 2013) a été présenté. En plus des brefs commentaires sur les articles présentés, le rapport général a examiné certains problèmes géotechniques des digues et des barrages. Pour les digues, la discussion est principalement ciblée sur l'érosion due au débordement, sur l'instabilité de l’écoulement interne et sur l’effondrement des rives. Pour les barrages, certaines technologies clés pour la construction de grands barrages en enrochement ont été présentées, qui incluent les propriétés des matériaux de construction, le traitement des fondations, le contrôle de la déformation du barrage et la fracturation hydraulique du noyau en terre.

KEYWORDS: dike, dam, gentechnical problems, general report

1 INTRODUCTION

Dike is a kind of very important structural approaches to flood management of rivers and lakes, and also to defense high tide alone seashores. To use dikes to protect land from annual floods date back centuries and in some places more than 2,000 years ago. Construction of a dike requires that it is high enough to exclude extreme flood and to avoid overtopping failure. Besides, as most of the dikes were constructed by earth materials and were normally found on natural riverbank, a common problem is seepage through the dike and foundation. The internal erosion by unfavorable seepage could lead to loss of dike or foundation materials and further lead to dike collapse and overtopping.

Rockfill dam is one of the most widely accepted and rapidly developed dam types in dam engineering. Rockfill dams in early stage were constructed by dumped rocks and face slabs. From 1920s to 1960s, with the progress of soil mechanics, earth core rockfill dam (ECRD) was well developed. The built dam height reached to 150m. After 1960s, with the application of vibrating roller and the technique of thin layer compaction, concrete faced rockfill dam (CFRD) was rapidly developed. Many high CFRD were constructed all over the world. At the same time, ECRD was further developed with the improvement of construction methods and equipment. At present, the dam height of CFRD has reached to 200m, while the height of ECRD has reached to 300m. CFRD and ECRD have become the main representative types of modern rockfill dam.

Dikes and dams are the important infrastructures in modern society. It is also an important field of the application of modern soil mechanics and geotechnical engineering. In conference ISSMGE 2013, there are 11 papers concerning dike and dam, which 5 paper on dikes and 6 papers on dams. For the papers on dikes, 2 papers are about seepage failure of dikes, with one paper for internal erosion and another paper for hydraulic failure; one paper is about settlement prediction; one paper for strength assessment of dike foundation material; one paper is about soil reinforcement of costal geotechnical engineering. For the papers on dam, two papers are about concrete faced rockfill dam, with one paper for numerical analysis and another paper for deformation control; two paper are about dam seepage, with one paper for the design of filter material and another paper for suffusion of loess material; one paper is about stability of earth dam; one paper is about the failure of tailing dam.

2 GEOTECHNICAL PROBLEMS OF DIKES

For dikes of flood defense, statistic analyses show that overtopping and internal erosion are the most common modes of dike failure. Besides, bank collapse is also one of the common threatens to the safety of dikes. All of these failure modes are the concern of geotechnical engineers in dike engineering.

2.1 *Flow erosion of overtopping*

When dike is not high enough to flood water level, overtopping will be happened. As most of the dikes are constructed by earth material, soil erosion by the flow of overtopping could cause the failure of the dike. Although no papers in ISSMGE 2013 have discussed this issue, it is still an important problem in dike engineering. In recently years, some overtopping cases were occurred and have finally led to the failure of the dikes. The dikes failure by Hurricane Katrina in 2005 in New Orleans, Louisiana, USA and Mississippi River levee failures by 2008 flood in USA are the typical cases of overtopping dike failure.

With occurrence of overtopping, the flow will erode the downstream side of the dike. Normally, soil erosion starts from the downstream toe of the dike, then develops upward to dike crest and finally lend to dike breach. The degree of damage depends on the depth and duration of overtopping as well as the soil properties. For geotechnical engineers, the more concerned issue is the impacts of soil properties on the flow erosion of overtopping. The overall index is the erodibility of the soil.

For the soils of dike, most of them are cohesive soil, the erodibility depends on its physic and mechanical properties, which include plasticity, water content, grain size, percent clay, compaction, and shear strength. In the study of soil erosion, Briaud has developed a method to determine the erosion function of a given soil (Briaud 2008). Based on this method, Michelle B. (2011) has conducted detailed investigation on the overtopping failure of Mississippi levee in the flood of June 2008 in USA. The studies have presented the levee overtopping case of the Winfield-Pin Oak site that was overtopped and severe erosion led to failure, and the Brevator site that was also overtopped but did not fail. By using Erosion Function Apparatus (EFA) (Briaud 2008), soil properties of plasticity index (PI), D50, and percent relative compaction were combined with EFA results to study the influence of these factors on the erosion resistance of a soil. Figure 1 presents the EFA results for the two levees. From the investigation and studies, it concluded that levee performance is influenced by the flood conditions, the site conditions, and the soil properties. Both sites in this study experienced large levels and durations of overtopping water, but it is proposed that the Brevator site survived because of its vegetative cover and more erosion resistant soils. Erosion is a very complicated phenomenon that cannot be described by any one parameter, but in all cases, dense and consistent native vegetative cover can greatly improve the overall levee performance.

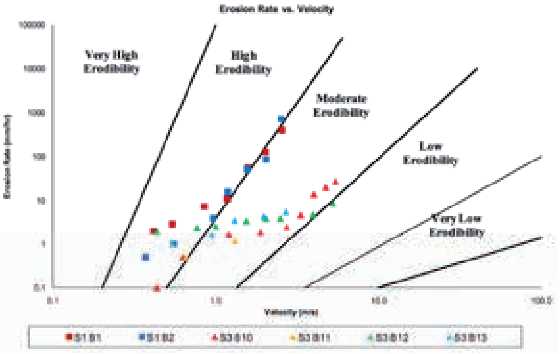

Figure 1 EFA results for Winfield-Pin Oak – S1 and Brevator – S3, Michelle B. (2011)

2.2 *Internal erosion*

Internal erosion caused by water seepage inside dike and foundation is a major failure mode of river dike damage. Actually, where there is a water head difference between upstream side and downstream side, there is seepage in the dike. With the rise of water level during flood period, the phreatic line is formed inside the dike and its position gradually rises up. At the same time, the seepage gradient in the dike and subsoil gradually increased. When the actual seepage gradient (J) is lager than the critical gradient of the subsoil (Jc), seepage failure is occurred.

As all the seepage failures are driven by hydraulic gradient, it could also be referred as hydraulic failure. The paper of H. Brandl has discussed the hydraulic failure of river dike, which include suffusion, contact erosion and internal erosion. The measures to avoid hydraulic failure are also presented in the paper. As internal erosion in dikes is not visible and difficult to be detected before the failure happened, the method of early diagnosis the possible internal erosion is significant in safety assessment of dikes. The paper of J. Monnet summarized the main methods for detecting dike internal erosion and presented the application of a new in-situ test, the Cross Erosion Test (CET), in Isère and Drac river levees in France.

Besides hydraulic conditions, the mechanism, procedure and the result of seepage failure have very close relation with the composition and properties of soil. Normally, dike seepage failures can be classified into 4 types: mass flow (all particles move by the force of flow), piping (fine grains flow though the channels of coarse particles), contact mass flow (erosion along the contact interface) and contact scouring. By analysis characteristics of soil gradation, the mode of seepage failure of each soil could be classified.

By large number of laboratory tests of different soils, Chinese scholars have summarized systematic methods to determine seepage mode of different soils.

According to the gradation, the non-cohesive soil can be classified into two types: homogeneous (Cu ≤ 5) and non-homogeneous (Cu > 5). For non-homogeneous soil, it can further be classified into two subtypes: discontinuous gradation soil and continuous gradation soil.

For homogeneous soil (Cu ≤ 5), there is only one failure mode: mass flow. For the non-homogeneous soil (Cu > 5), the failure mode depends on the gradation distribution. For soil with discontinuous gradation, the failure mode is determined by the content of fine grains (P). If P>35%, the failure mode is mass flow. If P<25%, the failure mode is piping. If P=25~35%, the failure mode is intermediate type. For the soil with continuous gradation, the failure mode is determined by content of fine grains method.

For the content of fine grains method, the content of fine grains at optimum gradation is introduced as an index. It is defined as:

$$P_{op} = \frac{0.30 - n + 3n^2}{1 - n}$$

n=porosity of the soil. If $P>1.1P_{op}$, the failure mode is mass flow. If $P<0.9P_{op}$, the failure mode is piping. If $P=(0.9{\sim}1.1)\ P_{op}$, the failure mode is intermediate.

The capability for resisting seepage failure is defined as the limit seepage force ($\gamma_w J$) that a unit volume of soil can be undertaken. The seepage gradient correspondent to this situation is the failure hydraulic gradient (J_n). Table 1 provides the summarization of allowed gradient and failure gradient.

Table 1 The range seepage gradient

J	Seepage failure modes				
	Mass flow		Intermediate	Piping	
	$C_u \leq 5$	$C_u > 5$		Continuous gradation	Discontinuous gradation
J_{fe}	0.8~1.0	1.0~1.5	0.4~0.8	0.2~0.4	0.1~0.3
J_a	0.4~0.5	0.5~0.8	0.25~0.4	0.15~0.25	0.1~0.2

For seepage safety of dikes, the primary goals of seepage control in dikes and foundation could be summarized as three aspects: (1) Decrease the quantities of seepage. (2) Release seepage pressure in advance for keeping the stability of foundation and geotechnical structure. (3) Prevent seepage failure of foundation and structure. Generally, the corresponding engineering measures are also includes three aspects:

·Seepage prevention: Put impermeable material in dike and foundation to cut the seepage passage and to decrease the water head in the dike and foundation.

·Drainage: Put permeable material as drainage at the certain places in the dike and foundation where the hydraulic gradient is relative large. To release the seepage pressure and let the seepage water freely discharge to downstream by the drainage.

·Filter protection: Filter is an effective measure for preventing seepage failure of soil. As it also has the drainage function, it is often as one part of the drainage. The materials for filter are natural sand and rock. But the material must satisfy following principals: □ filter material must be non-piping soil. □ the gradation relation between filter and protected soil must satisfy filter principals. □ the permeability coefficient of filter must larger than the protected soil. □ the coarse grains of the filter must hard and weathering resistant.

Figure 2 gives the typical engineering measures of seepage control applied in dike construction. The selection of theses engineering measures depends on the different situations of the dike.

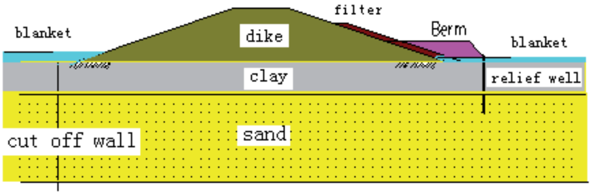

Figure2 Engineering measures of seepage control

2.3 *Bank collapse*

In nature rivers, the interaction of water flow and riverbank (upstream slope of dike) could cause bank erosion and bank collapse, which are the common damage to the safety of dikes. In USA, the total length of river channel is 5,600,000 km. About 800,000km riverbank were suffered of flow erosion, include bank collapse. In China, a severe bank collapse case has caused the lost of 115,000m^3 land. About half of a town was collapsed into river.

There are many factors that affect the occurrence of bank collapse, which include hydraulic features, properties of the materials of riverbed and river bank, features of river bank, impact of wind and wave, impacts of climate, impacts of human activities, etc. (Simons, 1982). For all these factors, water flow and boundary are the basic conditions.

For the mechanism of bank collapse, there are different viewpoints. Some scholars think water flow is the precondition of bank collapse. When the main stream of river approach riverbank, water flow will scour the bank and the bank slope will be steep. Some scholars believe the liquefaction of soil the cause of bank collapse. According to the force act on soil, the liquefaction of soil could be classified to shear liquefaction, seepage liquefaction and vibration liquefaction. If the dike is composed by non-cohesive sand or soils with less cohesion, its effective stress may drop to zero under the action of shear stress or seepage force. Some scholars explain the mechanism of bank collapse from the point of slope stability. Bank collapse occurred when upstream slope of the dike lost its stability. In flood season, soil of dike is submerged in water, which lead to the reduction of its shear strength. With the drop of upstream water level, the seepage force towards riverside and the reduced c, φ value could cause riverbank lost the stability.

As bank collapse is the result of the interaction of river flow and watercourse boundary condition, the engineering measures for avoiding bank collapse will mainly focus on water flow and watercourse boundary. For changing local water flow, groyne works are commonly employed. For improving boundary conditions, different bank protection method could be applied, which include riprap, concrete protection, geosynthetics, etc.

3 GEOTECHNICAL PROBLEMS OF ROCKFILL DAM

Rockfill dam is a widely applied dam type of dam engineering. The development of earth core rockfill dam in 1940s to 1960s is mainly based on the progress of the theory of soil mechanics. In recent years, more and more high rockfill dam will be constructed. New challenges on geotechnical engineering problems are encountered in the construction of those high dams.

3.1 *Construction material*

The construction materials of rockfill dam include impervious material, filter/transition material, and rockfill material. Proper application of the construction material according to its engineering properties is one of the key issues for rockfill dam design.

3.1.1 Impervious material of earth core

For high ECRD, earth core will subject to high stresses. Ordinary clay material could not meet the strength and compressibility requirements of high dam. Therefore, for most ECRD with the height above 200m, the core material uses gravelly soil. As for the composition, gravelly soil is mixture of clay and gravels with the grain size larger than 5mm (or 2mm). Soil of weathered rock and glacier deposit are also a kind of gravelly soil.

(1) Gradation adjustment for gravelly soil of core material

Generally, if the soil has more than 20% coarse grains content, i.e. the grain size larger than 5mm, it could be classified as gravelly soil. Those soils include various soils with gravels, clay gravel and weathered rocks.

The composition of nature formed gravelly soil is very inhomogeneous. When it is used as core material, its gradation and water content are often need to be adjusted by the requirement of design.

For nature gravelly soil with wide range of gradation, if the material is basically applicable, the oversize particles could be removed to increase the content of fine particles. The case for applying this measure is Pubugu ECRD in China.

The impervious material for the central core of Pubugou ECRD is the gravelly soil with wide range of gradation. The coarse grain content is 50%~65% and the content of particles with the size less than 0.1mm is 8.8~20%. In soil classification, the material is GP. The permeability of the material after compaction is 10^{-4}~10^{-5}cm/s, which is not fit the requirement of impervious material of high dam. With series studies, two measures were employed for improving the properties of the material, which are: adjust gradation by removing the particles with the size larger than 80mm (or 60mm) and use modified Proctor compaction energy to increase its density.

After removing the particles of the size larger than 80mm form the nature wide range gradation gravelly soil, the gradation of the material was improved significantly. The content of particles of the size less than 5mm was 50%, and the content of particles of the size less than 0.1mm was 22%. Classification of the material was change from GP to GC. Permeability of the material reached to 10^{-5}~10^{-6}cm/s. With the protection of filter material, the hydraulic gradient of seepage failure was 60~100.

By using heavy compaction standard (modified Proctor compaction), the compaction energy is increased from 604kJ/m^3 to 2704kJ/m^3. Accordingly, the maximum dry density of the material is increased from 2.23~2.32g/cm^3 to 2.375g/cm^3. The permeability of the material is less than 1×10^{-5}cm/s and the deformation modulus is also remarkably increased.

For borrow soil mainly composed by fine grains, the material usually cannot fit the stability and deformation requirement of high dam. In this case, gravels or crushed rock should be added to increase the content of coarse grains. The case for applying this measure is Nuozhadu ECRD in China.

The borrow materials of Nuozhadu ECRD is mixture of slope washed, residual soil and some strongly weathered rocks. The average grain composition is: 24% gravels with the size larger than 5mm, 44.3% fine grains with the size smaller than 0.074mm, 21.7% of the grains with the size smaller than 0.005mm. Most of the soils are classified as clay sand, low liquid limit clay with sand. As most of the grains are weathered sandstone and mudstone, grain particles are easily broken. After compaction, the content of grins with the size larger than 5mm could be reduced to 10%. The density, deformation parameters and shear strength of the material are very low. Thus, it is decided to add crushed hard rock to the nature borrow material.

The size range of crushed rock to be added in borrow material is 5~60mm. After optimization, proportion of the adding material is 35%. From the research results, after adding coarse particles, content of the grains with size larger than 5mm is 50%, content of the grains with size smaller than 0.074mm is 23.6%, content of the grains with size smaller than 0.005mm is 10%. The classification of the mixed material is GC. It is an idea impervious soil for high ECRD. Due to the breakage after compaction, the content of grains larger than 5mm could be 36%. Compare with the unmixed material, the maximum dry density could be increased from 1.7~1.8g/m^3 to 1.9~2.0g/m^3. The corresponding water content is about 10%~15%. The overall engineering properties of the material are greatly improved.

(2) Gradation and permeability of gravelly soil

The permeability of gravelly soil has close relationship with its gradation. For high ECRD, the general requirement is: the content of grains with size larger than 5mm should not above 50% (or should below 60%), the content of grains with size smaller than 0.075mm should not below 15%, and the content of clay grains should not below 8%. But in practices, due to the wide range gradation of natural gravelly soil, the above principles could be adjusted according to the real situations. By the analysis from the point of geotechnical engineering, the requirement of content of grains with size larger than 5mm should not above 50% is to guarantee the void of coarse grains could be filled by fine grains. The requirement of content of grains with size smaller than 0.075mm should not below 15% is to guarantee the low permeability and to keep internal stability of soil structure under seepage flow. As for the requirement of the permeability of impervious soil, when it is in the quantity of 10^{-5}cm/s, the actually leakage is quite small. It is unnecessary to request the permeability to be 1×10^{-5}cm/s. As for the seepage stability, normally, the gravelly soil with wide range gradation will have less clay grains. Thus, it has the same properties in seepage deformation as non-cohesive soil. The hydraulic gradient for seepage failure resistance of gravelly soil is mainly depends on the filter at the exit. With the protection of filter, the failure gradient can be improved significantly. Therefore, the content of clay grains above 8% could not be an unchangeable rule. For the case of Pubugou ECRD, the material has 17%~48% grains with the size smaller than 1mm and 4%~12% clay grains. Under normal compaction, the tested maximum hydraulic gradient could reach 90~140.

(3) Compaction of gravelly soil

The two methods for soil compaction quality control are dry density and compaction degree. In compaction, gravelly soil presents the properties of both gravel and clay. For the compaction of gravelly soil, it is required to get the maximum dry density of the full material and also to check the dry density of fine grains. By considering the variability of the soil, compaction degree is more often to be used as the index for quality control of gravelly soil compaction.

For the mixed soil with coarse and fine grains, besides the compaction degree of full material, it is also has the compaction degree of fine grins. As the compaction degree of fine grains mainly controlled the permeability and mechanical property of gravelly soil, it is unnecessary to conduct difficult large-scale compaction test for full material. When content of coarse grains is below 60%~70%, the dry density of full material will be increased with the increasing of coarse grains content. When content of fine grains is below 20%~30%, the coarse grains will not take the function of soil skeleton. The fine grains are fully compacted. Its dry density keeps unchanged. When content of fine grains reaches 30%, the coarse grains start to take function of skeleton. The more content of coarse grains, the stronger is its skeleton function. Thus, the fine grains inside void cannot be fully compacted. The dry density of soil will be reduced with the increase of coarse grains. When content of coarse grains is 60%~70%, the skeleton function of coarse grain is fully realized. The dry density of full material and fine grains reduced synchronously. All its mechanical properties are dropped in big scope and the permeability of soil are increased rapidly. Therefore, in the application of compaction degree control of fine grains, when content of coarse grains is below 25%, the compaction degree for fine grains could be controlled with 100%; when content of coarse grains is 25%~50%, the compaction degree control for fine grains could be reduced to 97%~98%.

3.1.2 Filter material

The process of seepage failure in soil is always started from exit, and gradually developed to the inside, then finally lead to local failure or whole structure failure. Using filter to control seepage exit is an effective seepage control measures in dam engineering. It could be a drainage zone and also to prevent fine grains flow out. For high ECRD with gravely soil as the core, although gravelly soils have certain content of clay grains, it is still belong to the soil without plasticity or with low plasticity. The filter design should also follow the principle of no fine grains been washed out. The paper submitted by S. Messerklinger discussed the functions of filter in geotechnical structures and summarized the main principles of filter design. Figure 3 is the summary of the design criteria of filter design (Messerklinger 2013). The paper submitted by R. Eerzariol presented the test studies on filter protection of loess, a kind of sandy silt that largely distributed in central Argentina. The studies suggested that filter with fines content between 15% and 25% perform the best condition of seepage stability for protecting silt core (Eerzariol 2013).

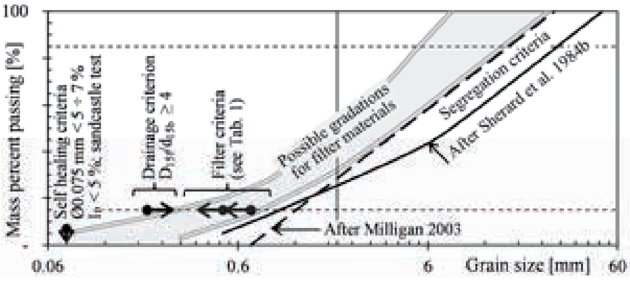

Figure 3 Design criteria of filter (Messerklinger 2013)

For high ECRD, the seepage stability of gravelly soil depends on many factors. Besides gradation, dry density, stress level and downstream protection are all have impacts on the internal stability of soil upon seepage flow. Normally, the mixture of sand, gravel and fine grains with good gradation will present good erosion resistance. For gravelly soil, if the content of coarse grains (>5mm) below 50%, the content of clay grains (<0.075mm) above 15%, and the material is well compacted, the gradient for resisting seepage failure will be relatively high. But in practice it should be aware that due to the variability of gravelly soil, the result obtained by calculation must be checked by filter test.

3.1.3 Rockfill material

Rockfill is the main construction material of rockfill dam. Its strength properties are related with dam slope stability and its stress-strain properties are related with dam deformation. From the experience of modern rockfill dam construction, deformation control is the most important issue to be considered. For high rockfill dam, rockfill with high or medium rock strength, i.e. the saturated uniaxial compressive strength is 30~80MPa, should be the best choice. For getting high compaction density, the rockfill should also have good gradation. From the point of deformation control and deformation coordination, rockfill for CFRD should have as high compaction density as possible. The purpose is to reduce the overall deformation quantities. For ECRD, the consideration in rockfill selection is more emphasized on deformation coordination between dam shell and earth core.

The particle shapes of rockfill material are usually polyhedron. Most of the particles are contacted by point. The compressibility of rockfill mainly depends on re-arrangement of particles, and it is also affected by other factors such as rock lithology, density, gradation, etc. Due to the granular characteristic of rockfill material, grain breakage and particles rearrangement is occurred at any moment during loading process. That means the status of rockfill material will be changed all the time. Therefore, the material properties will not be a constant value. For low dam, as the relatively low stress level of rockfill, the breakage of particles is not significant and most of the deformations are occurred during the stage of compaction. For high dam, due to the high stress level and complicated stress paths, the breakage and rearrangement of particles cannot be neglected. The process of the particles breakage and particles movement will lead to a significant increase of the post-construction deformation of rockfill. At present, this post-construction deformation of rockfill cannot be fully analyzed by existing models and methods. For correctly describe the change of status of rockfill material that caused by particles breakage and rearrangement, the properties of particles breakage of rockfill material must be fullly studied, and the new analysis models will be further developed.

For rockfill, another important characteristic is the wetting deformation property of the material. The mechanism of wetting deformation of rockfill is the inteneration and breakage of the edge of rockfill particles under the action of water. Besides, the lubricating action of water promotes the movement and rearrangement of the particles. Thus, it leads to the additional deformation. The wetting deformation of rockfill is directly related with its lithology. Normally, soft rockfill has relatively large wetting deformation. But it is noticed that even for the hard rockfill, such as limestone and tuff, the wetting deformation still cannot be neglected. The wetting deformation of rockfill will be reduced with the increasing of its density. In addition, the more of initial water content of rockfill, the less wetting deformation. Therefore, adding water during rockfill compaction will play an important role in speed up deformation completion and reducing post-construction of rockfill.

Correctly predict deformation of rockfill dam depends on the constitutive model used in numerical analysis. The paper submitted by Y. Chen used an elasto-plastic model that takes into account irreversible deformations of poorly or well-compacted rockfill under deviatoric and isotropic loading of rockfill, known as L&K-Enroch, developed by EDF-CIH (Chen 2013) to conduct 3D numerical analysis of Mohale CFRD in South Africa.

3.2 *Foundation treatment*

Foundation or subsoil condition is very important to the safety of dam. Before the construction of dam, the unfavorable layer in foundation must be properly treated. The paper submitted by J. Mecsi presented a failure case of tailing dam in Hungary (Mecsi 2013). The foundation of the dam has a sand-silt layer that may move under high water condition. Figure 4 is the summary of some effects for the failure of the tailing dam. It shows the impact of the unfavorable subsoil on the safety of the dam.

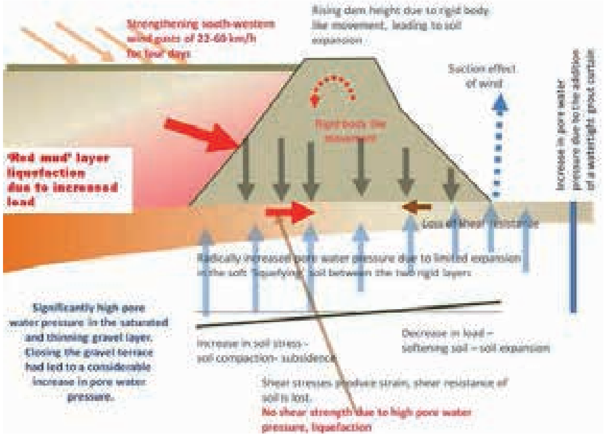

Figure 4 Summary of the effects for tailing dam failure

The foundation of high rockfill dam includes bedrock foundation and alluvium foundation of sandy gravel deposit. For the sandy gravel alluvium, if the alluvium has no soft, weak clay layers or silt, fine sand layers, the bearing capacity and stability of the foundation can be guaranteed. The main task of foundation treatment is seepage control. If the lower part of alluvium foundation exist sand layer, the possibility of sand layer liquefaction should be carefully assessed.

For high rockfill dams, the commonly accepted seepage control measure for foundation treatment is vertical cut off. It could effectively block the seepage though pervious alluvium foundation. With the measures of filter and drainage at downstream seepage exit, the foundation and dam body will not subject to seepage failure.

For high rockfill dam with deep alluvium foundation, the most effective vertical seepage control measures are excavation of all the alluvium layers under the impervious part of the dam or using concrete diaphragm wall to cut the seepage though foundation. Recently, concrete diaphragm wall is accepted for most of the high CFRD constructed on deep alluvium foundation. For this application, the diaphragm wall is connected with plinth via concrete slabs (Xu 2010). For high ECRD, both measures as alluvium excavation and concrete diaphragm wall are applied.

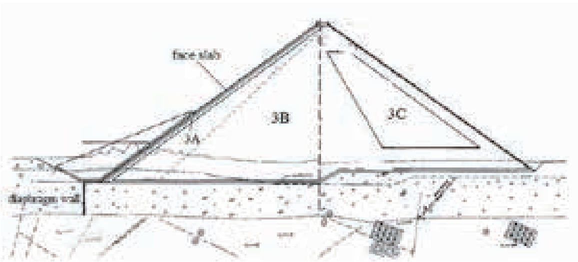

Figure 5 CFRD built on alluvium foundation

For high ECRD with the application of concrete diaphragm wall for seepage control, one of the key issues is the connection of diaphragm wall, earth core and gallery, and also the connection of gallery with abutments. Generally, directly insert diaphragm wall into earth core is more technically reliable. When the top of diaphragm wall is connected to earth core by gallery, differential displacement could be produced between the wall and gallery. Joints should be arranged for the connection. Also, the connection of gallery and abutments should also arrange joints for adapting large differential displacement.

For rock foundation, when bedrock exists geological defects such as permeable stratum, fault fissures filled with erodible materials, solution fissures or caverns, curtain grouting or curtain grouting combined with consolidation grouting are necessary. In design standard, the depth of grouting should reach to impermeable layer. The permeability of rock stratum is represented by Lugeon value (Lu). Usually, the value of 3~5 Lu could be applied for most of the rockfill dams foundation.

3.3 Control and coordination of dam deformation

In the design and construction of high rockfill dam, deformation control is the most important issue. The stress statuses of watertight barrier and dam operation performance are all related with dam deformation. Therefore, the concept of integrated deformation control and deformation coordination should be a principle for the design and construction of high rockfill dam. The main focus of this new concept includes two parts: (1) to reduce the total quantities of dam deformation, (2) to coordinate differential deformation between different zones.

Taking the example of CFRD, the ultimate purpose of deformation control and deformation coordination will be the safety of concrete face slabs and joint system. It could be expressed as:

$$\sigma_t < \begin{Bmatrix} \sigma_s \\ \\ \sigma_a \end{Bmatrix} < \sigma_c \qquad \begin{Bmatrix} \max(DP_o) \\ \max(DP_s) \\ \max(DP_d) \end{Bmatrix} < \begin{Bmatrix} D_o \\ D_s \\ D_d \end{Bmatrix}$$

Where: σ_t and σ_c are tensile and compressive strength of concrete; σ_s and σ_a are stress of face slab in the direction of dam slope and dam axis; DP_o, DP_s, DP_d are displacements of joint and D_o, D_s, D_d are upper limit of joint displacement.

For high CFRD, the general principles of the integrated deformation control and deformation coordination could be summarized as follows:

The deformation of rockfill is directly related to lithologic character, rockfill gradation, compaction density, dam height, valley shape, etc.

In the design and construction of high CFRD, the low compressibility and good gradation rockfill material should be selected, and the compaction density should be strictly controlled to reduce the overall deformation quantities of rockfill.

In the design of high CFRD, material zones should be arranged to achieve the coordination of deformations of different parts of the dam.

In the construction of high CFRD, the construction stages of rockfill and face slab should be well arranged to provide sufficient time for deformation stabilization of upstream rockfill.

The above principles could be expressed as:

$$S=F(H,H/A^2,n,S_c,C_s)$$
$$n \le n_l$$
$$g \le s_p, \quad E_u/E_d \le r$$
$$T \ge t_p$$

Where: S is the maximum settlement of rockfill, H is dam height, A is area of face slab; n is rockfill porosity (represent compaction density); S_c is uniaxial compressive strength of rock (represent lithologic character); C_s is coefficient of uniformity (represent gradation of rockfill).

From the analysis of monitoring data and numerical analysis, the control of rockfill deformation quantities could be represented by the ratio of maximum settlement of rockfill to the height of the dam. For CFRD with the height above 200m, d is recommended to be controlled to 0.8%~1.2%, that is:

$$S=dH \ (d=0.8\%\sim1.2\%)$$

n_l is the standard for rockfill porosity control. For CFRD with the height above 200m, n_l is recommended to be controlled fewer than 20%. 18%~20% is more favorable.

S_p is the slope of the boundary between zone 3B and 3C. For high dam, the boundary line should incline to downstream side. The slope should not steeper than 1:0.5, i.e. $S_p \ge 0.5$.

r is the ratio of modulus of upstream and downstream rockfill. For CFRD with the height above 200m, the modulus ratio of upstream rockfill and downstream rockfill is recommended be controlled below 1.5 to coordinate deformation of upstream and downstream rockfill, i. e. $1.0 \le r \le 1.5$.

t_p is the time for upstream rockfill deformation completion. To reduce the impact of rockfill deformation on stresses of concrete face slab, certain period of time for rockfill deformation should be provided before the construction of concrete face slabs. Normally, the time is not less than three months, i.e. $t_p \ge 3$ months. On the other hand, as the criteria for assessing the completion of upstream rockfill deformation, monthly settlement rate of less than 3~5mm is the recommended as control values.

In addition to the control of deformation quantities, the new concept more emphasizes on the coordination of deformations between different dam zones. For high CFRD, it includes the deformation coordination for the rockfill of upstream and downstream, abutment area and riverbed area, upper part and lower part, and also, the deformation coordination of concrete face slab and upstream rockfill, and rockfill constructed in different stages. For high ECRD, the focus is on the coordination of deformation of rockfill shell and earth core to avoid harmful cracks on earth core.

In the paper submitted by N. Li, the methods for assessing deformation coordination of CFRD were proposed, which include settlement, horizontal displacement and deflection of concrete face slab (Li 2013). The propose concept was applied in the design and construction of Bakun CFRD. In the paper submitted by Y. Chen, three-dimensional numerical analysis of a high CFRD was presented. From the results of analysis, it is noticed that the large deformation of rockfill and differential displacement between rockfill and face slabs will cause the cracks on concrete face slabs (Chen 2013).

3.4 Hydraulic fracture of high ECRD

For high ECRD, the failure of earth core by hydraulic fracture is one of the key issues that concerned by dam engineers. And, it is also a controversial problem in geotechnical engineering. At present, the mechanism and criteria for hydraulic fracture are still questions and disputes among engineers and scholars.

From the analysis, the mechanism of hydraulic fracture is the crack developed under the condition of effective stress reduces to its tensile strength by the action of water load. The failure of hydraulic fracture is the process of outside water acting on the initial cracks to produce continuous extension of the cracks, and then finally run through the whole earth core. From the traditional point of view, when the increase of pore pressure leads to tensile effective stress of the soil, hydraulic fracture will be occurred. But, it should be noticed that many reasons could lead to the tensile effective stress. Only the reduction of effective stress is caused by external water load, the produced cracks are considered as hydraulic fracture.

From numerical analysis, it could be observed that the direction of principle stress on upstream surface of earth core is deflected due to the “arching effect” of dam shell. Upon reservoir impoundment, with the upstream water load, the direction of principle stress will be further deflected. The direction of major principle stress turns to parallel with the direction of water pressure. In this case, when the effective minor stress of the earth core reduced to the tensile strength of the soil by the action of water pressure, horizontal cracks will be produced. This could be the cause of hydraulic fracture.

When the initial cracks of hydraulic fracture are produced on the surface of the earth core, the further development of the cracks depends on many factors, which include hydraulic gradient, stress status and permeability of the soil, etc. The final failure mode of hydraulic fracture is soil erosion by seepage.

4 SUMMARY

Both in the field of dikes and dams, geotechnical problems are the essential engineering issues. Problems such as soil erosion by water flow, internal instibility by seepage, settlement and seepage control, foundation treatment are all related with the geotechnical properties of soils. With the changing situations and the development of modern dam engineering, more and more challenges will be encountered. Geotechnical engineering is a subject based on engineering practices. To solve the geotechnical problems in engineering, the basic principles of soil mechanics should be followed. Furthermore, the new concepts and methods are also need to be developed by systematic studies and careful observations.

The 11 submitted papers in the field of dikes and dams have covered relatively wide range of the studies and represented main concerns both in dike engineering and dam engineering.

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