FEATURE

2nd Ir. CHIAM TEONG TEE MEMORIAL LECTURE

CHINGFORD RESERVOIR FAILURE AND EFFECTIVE STRESS: FROM TERZAGHI TO BISHOP


Ir. Dr Ooi Teik Aun *Ir. Dr Wang Hong Kok*

The speaker, Prof. Dr Laurence D. Wesley has 50 years' working and teaching experience in Indonesia, Malaysia and New Zealand. He was consulted in foundation building designs in Kuala Lumpur, the Sungai Layang Earth Dam in Johor Baru, KL-Karak Highway, and Kuala Krai-Gua Musang Highway. He has also written four books.

The second Ir. Chiam Teong Tee Memorial Lecture held at Wisma IEM Chin Fung Kee Auditorium on 23 June, 2018, was titled "Application of Effective Stress – From Terzaghi to Bishop". The lecture was supported by Geotechnical Engineering Technical Division and managed by IEM Academy Sdn. Bhd. This report relates the application of effective stress in dams, particularly the Chingford Reservoir failure.

Man started building masonry dams as early as 4,000 BCE in the Black Desert of modern Jordan for irrigation of agricultural products (Brown and Jackson, 2018). Over time, as population expanded, more dams were built for water consumption, generating hydroelectric power and recreational purposes. However, building dams can incur high costs, require high technical skills and, above all, invite high risks. Zhang, Xu and Jia (2009) compiled a list of around 900 dam failures since 1800 – some 65.5% are earth dams. According to the report, there was a particularly high failure rate in the 1880-1979 period.

On 23 July, 2018, the earth-filled Saddle Dam D in the Champasak Province of Laos collapsed while still under construction. It resulted in 40 people dead, 100 missing, and 6,600 others being displaced as well as great suffering to the affected villagers (BBC News, 24 July, 2018). More accounts of dam failures may be found in Foster, Fell & Spannagle (2000), and Sharma & Kumar (2013)'s articles.

In the London BOROUGH of Enfield, United Kingdom, work began on Chingford Reservoir in 1936. A major slip appeared during the construction when the 20m-wide embankment fill height reached 7m. The slip caused a 71cm drop, pushing forward the embankment by 4m (Figures 1 and 2). Soon after the incident, Dr Herbert Chatley and Prof. Karl von Terzaghi were appointed to find out the causes and to suggest ways to avoid future ocurrences.

Figure 1: Chingford Slip, London
Source: Tedd (2015)

During a British Dam Society talk on 5 October, 2015, Paul Tedd said at least three factors could have contributed to the Chingford slip: "The presence of soft weak clay in the foundation, undrained shear strengths of 10 to 14kPa, development of high pore pressure due to rapid construction and little dissipation of pore water pressure."

During the lecture, Prof. Laurence also discussed the soil properties of the Chingford Reservoir. He noted that the construction of a nearby reservoir went on smoothly by adopting one-third the rate to infill, compared to the Chingford Reservoir's fast speed via modern bulldozers,

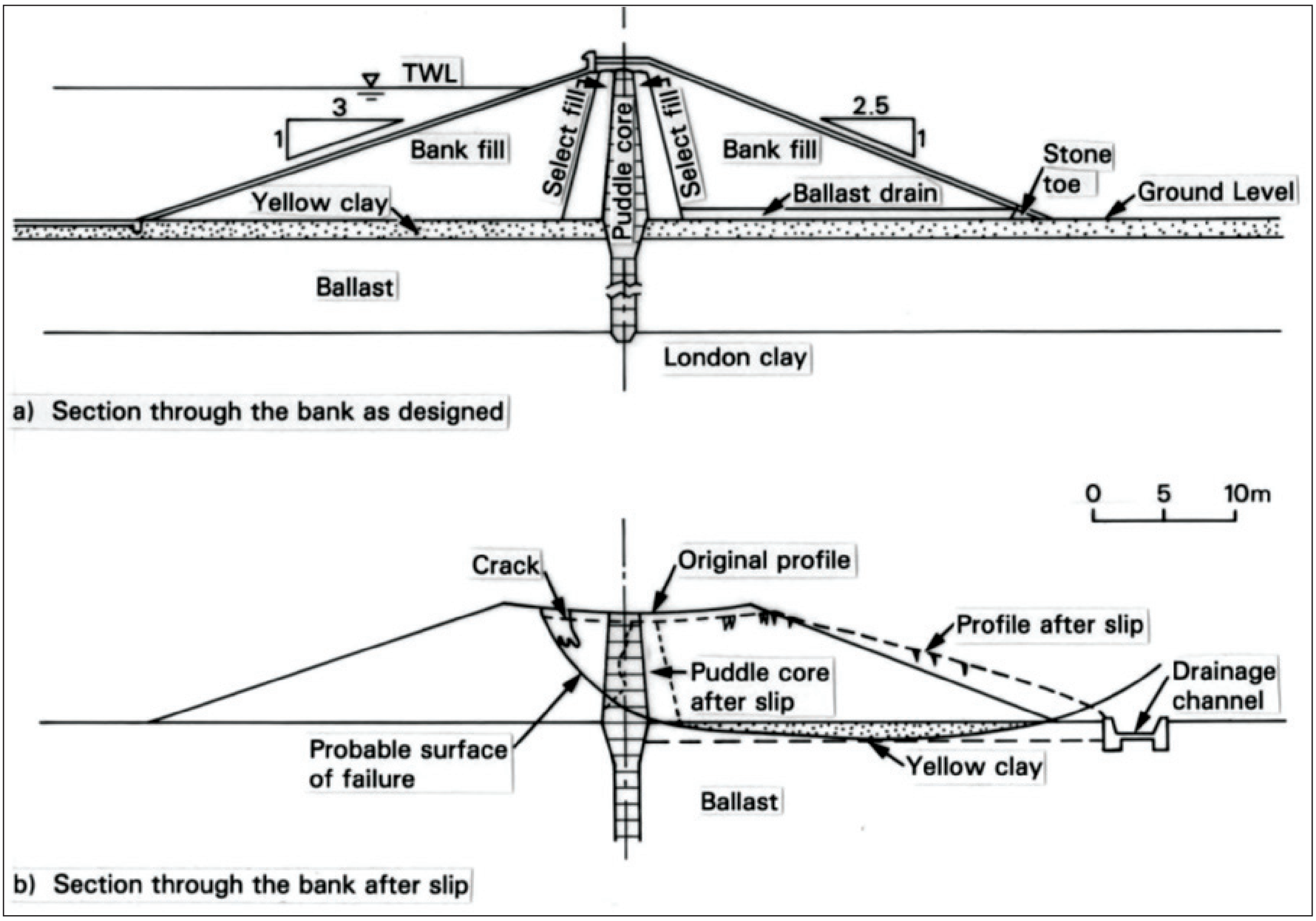

Figure 2: Shear failure during construction, Chingford Reservoir, London
Source: Tedd (2015)

which accelerated the embankment construction. The principle of effective stress was also referenced in his talk.

The aim of this short article is to appraise the role of effective stress in embankment stability analysis. Three questions were raised: What are Karl von Terzaghi's contributions to soil mechanics? What are Alan W. Bishop's contributions to the principle of effective stress? How can the concept of effective stress be used in practical situation? The following is an excerpt taken from Prof. Laurence's lecture.

KARL VON TERZAGHI

Prof. Laurence observed that the earliest understanding of dry sand soil properties came from Coulomb's work, as seen in the formula:

$$s = c + \sigma \tan \phi$$

Where s is shearing resistance, c is the cohesion, ϕ is angle of internal friction, and σ is the normal stress on the shear surface. Shearing resistance refers to a measure of shear stress, where shear stress is the average normal intergranular contact force per unit area. Shear stress is a function of effective stress, drainage conditions, density of the particles, the rate of strain, and the direction of the stress (Wikipedia, 2018).

Sand and clay are different in many aspects. Prof. Laurence explained that moving from sand to clay can pose challenges since clay consists of two major elements, water and solid particles, which could act both independently and interdependently. The nature of solid particles can be hard or soft. "It was Terzaghi who first came out with the basic principle at the heart of modern soil mechanics, known widely as the principle of effective stress" said Prof. Laurence.

Terzaghi was born in Prague, Austria, in 1883. He studied at Graz Technical University and worked in Vienna and Istanbul. He taught in Harvard University after World War 2 and established an impressive career till his death in 1963.

Prof. Laurence noted that Terzaghi was famous for two contributions: First, Terzaghi investigated vigorously soil properties in field settings. Second, he conducted laboratory tests to develop theories to explain field performance of soil. Terzaghi co-authored with Ralph B. Peck, a widely used text book, "Soil Mechanics in Engineering Practice" in 1948. See also GeoStructure (2015)'s article for further information about Terzaghi.

ALAN W. BISHOP

Bishop was born in 1920 in Canterbury, England and grew up in Whitstable. He was educated in Cambridge University. Bishop worked briefly for the London Metropolitan Water Board in 1943 and established a "rigorous procedure for applying the results of triaxial tests to the analysis of practical stability situations".

In 1946, he and his colleague, Skempton, moved to Imperial College which they helped develop into a worldwide famous centre of the learning for soil mechanics.

"Though Bishop was well known for pioneering his slip circle, Bishop Method, he was better recognised for establishing the relevance of the principle of effective stress to practical situations," said Prof. Laurence.

THE PRINCIPLE OF EFFECTIVE STRESS: BISHOP

In a landmark article on "The relevance of the triaxial test to the solution of stability problem", Bishop & Bjerrum (1960) defined the role of effective stress which can be used under different condition sets.

Basically, $\sigma' = \sigma - u$ where σ' is effective stress, σ is total stress, and u is pore water pressure. σ' of soil is affected by change in effective stress, but change in soil volume/strength is due to change in effective stress.

Table 1 is a summary of the formula calculations for shear strength and volume change.

Table1: Shear Strength and Effective Stress

VOLUME CHANGE	SHEAR STRENGTH
$\Delta V/V = m_v (\Delta\sigma - \Delta u) = m_v\Delta\sigma'$	$r = c' + (\sigma - u) \tan\phi'$ $= c' + \sigma' \tan\phi'$ …… 1
Where mv = one dimensional coefficient	In the equation 1, r is shear strength, c' is cohesion intercept, ϕ' is angle of shearing resistance. c' and ϕ' are in terms of effective stress

Source: Prof. Laurence's Lecture

There is another way to determine shear strength: Direct measurement without any change in water content. Prof. Laurence said: "For fully saturated soils, this means that no change in effective stress is occurring. This strength is thus a constant, known as the undrained shear strength, (not the cohesion) usually denoted C_u or S_u."

Figure 3 shows the results of undrained triaxial tests on fully saturated soil. "With such tests, the strength measured is independent of the cell pressure, which is the total normal stress acting on the sample," Prof. Laurence added.

Table 2 gives a summary of Bishop & Bjerrum (1960)'s observations on choices of geotechnical engineers in analysing a stability situation. Readers may read more about triaxial tests in Bishop & Henkel (1957)'s article.

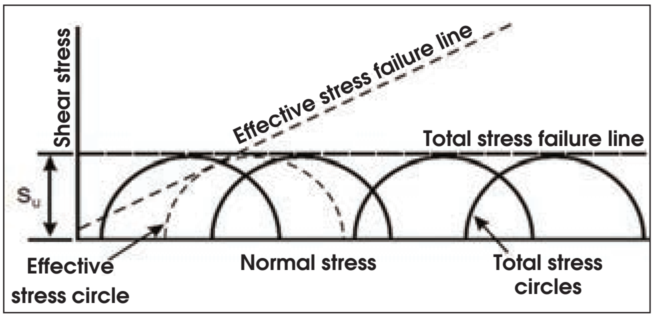

Figure 3: Undrained Triaxial Tests on a Fully Saturated Sand
Source: Prof. Laurence's Lecture

Table 2: Choices available in analysing a stability situation

	METHODS	CASES
Undrained condition	An undrained (or total stress) analysis based on undrained shear strength S_u (originally called $\phi = 0$).	The "End of construction" or "Immediate" case stability estimate using total stress analysis based on low permeability of clay. Undrained strength does not change during construction.
Drained condition	A drained analysis based on effective stress, based on c' and ϕ'.	The 'Long term" case. Stability estimate using an effective stress analysis.

Source: Prof. Laurence's Lecture

EFFECTIVE STRESS IN PRACTICAL SITUATION

Through a self-explanatory diagram (Figure 4), Prof. Laurence drove home his argument on how to select the correct method in the design analysis.

First case (Figure 4): As a building is built sitting on a surface foundation, the building load increases the confining stress on the soil. As water is being squeezed out of the soil, the strength increases. Herein, the foundation design should be based on the initial strength of the soil — that is, the undrained shear strength (S_u). See Table 2. Through time the margin of safety increases.

Second case (Figure 4): If excavation is needed to make way for a highway, it reduces the load and the confining stress on the soil, causing reduction in pore pressure in the soil. Water then seeps towards the excavation area which will decrease soil strength and lower the safety margin. Herein effective stress is recommended in the design analysis (Table 2).

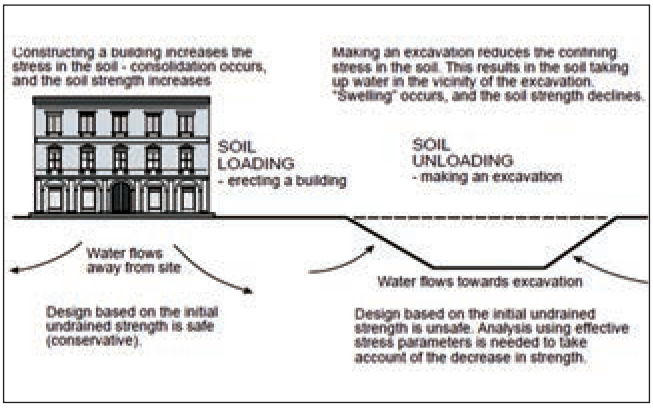

Figure 4: Different Stress Applications Requiring Different Methods of Analysis
Source: Prof. Laurence's Lecture

CONCLUSION

This article discusses the contributions made by Terzaghi to soil mechanics, Bishop's contributions to the principle of effective stress and the concept of the effective stress used in practical situations.

Prof. Laurence closed his lecture with a cautionary remark referring to Terzaghi's observations delivered in the first international soil mechanics conference in 1936, herein reproduced:

"However, as soon as we pass from steel and concrete to earth, the omnipotence of theory ceases to exist. In the first place, the earth in its natural state is never uniform. Second, its properties are too complicated for rigorous theoretical treatment. Finally, even an approximate mathematical solution of some of the most common problems is extremely difficult". ■

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