

What remains true about hydraulic heave hundred years after the publication of Terzaghi's book "Erdbaumechnik"?

Markus Herten

Lehr- und Forschungsgebiet Geotechnik, University of Wuppertal, Germany, herten@uni-wuppertal.de

Bernhard Odenwald

Federal Waterways Engineering and Research Institute, Germany

ABSTRACT: Terzaghi wrote his first book *Erdbaumechnik* during his stay at the Robert College in Istanbul in the 1920's. One hundred years after the publication of this seminal book, this article examines which of Terzaghi's contributions to soil mechanics remain relevant today. Terzaghi's proposal for the verification against failure due to hydraulic heave will be included in the next generation of the Eurocodes. However, not all of his findings presented in his first book have been adopted as geotechnical rules. Even in his later publications, some details of this first book were lost, for example, the original requirement to vary the depth of the soil body to be analyzed. Initially, he specified that only in the special case of groundwater flow below a sheet pile wall in homogeneous soils the depth of the analyzed soil body should extend to the toe of the sheet pile wall. Also, his description of "Kraftlinien", which can be understood as the directions of maximum principal stresses, was visionary. Today, it is possible to use FEM to calculate the changes in stress in the soil as a result of groundwater flow. Terzaghi has developed drawing rules in order to be able to represent these stress directions as an analogue to flow path. Despite these omissions, many aspects of Terzaghi's first book remain relevant. The benefits and dimensioning of filter loads were described in detail in Terzaghi's first book and are still valid today, as shown in this article. Finally, one should not forget his warning with respect to backward erosion. Based on failure histories, it has been proven that this usually happens before a hydraulic heave can occur. The article highlights the genius of Terzaghi and how he achieved fundamental geotechnical knowledge with simple means. What would he have been able to achieve with today's tools?

KEYWORDS: hydraulic heave, surcharge filter, regressive erosion, Eurocode, Terzaghi.

1 INTRODUCTION

100 years ago, Karl Terzaghi published his groundbreaking work "*Erdbaumechnik auf bodenphysikalischer Grundlage*" (Terzaghi, 1925) in Istanbul. This work is considered a milestone in soil mechanics. In it, Terzaghi not only laid the theoretical foundations, but also developed practically applicable methods for proving safety against geohydraulic hazards such as hydraulic heave and backward erosion. Today, in the age of numerical methods and comprehensive, normative design regulations, the question arises as to which of his findings on the hazards caused by groundwater flow to the ground of structures and earthworks are valid, which are outdated and whether some of his concepts - for example his use of force lines and the concept of filter load - are gaining new relevance. The aim of this article is to systematically examine Terzaghi's findings, compare them with current developments and assess their significance for future Eurocodes.

2 VERIFICATION OF HYDRAULIC HEAVE

As early as 1922, Terzaghi developed a methodically consistent procedure (Terzaghi, 1922, later integrated into Terzaghi, 1925) to assess the safety against hydraulic heave. For this purpose, he considers the interaction of dead weight and rising flow pressure in the soil body under a dam. He makes a clear distinction between the buoyancy zone and the earth pressure zone (Figure 1).

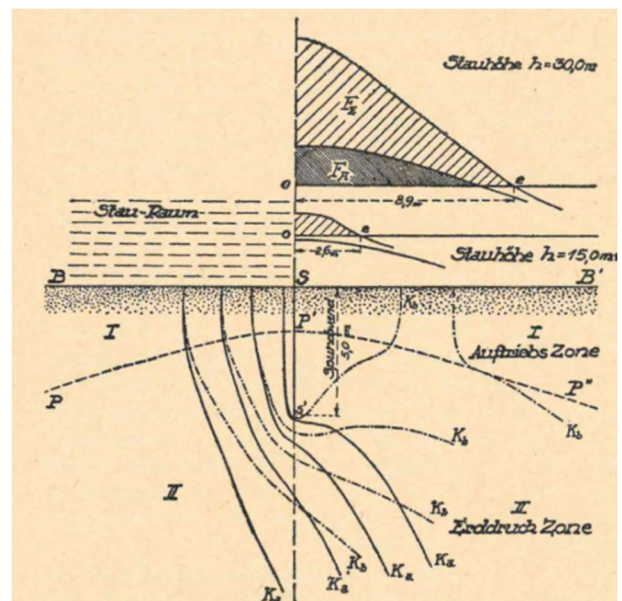


Figure 1. Buoyancy zone and earth pressure zone in the underflow of a dam to determine the maximum dam height without and with surcharge filter (Terzaghi, 1925, Fig. 63)

With this concept, he also differentiated for the first time between subsurface erosion (regressive erosion) and piping by heave (hydraulic heave). While in subsurface erosion the particles are flushed out at the exit point, in piping by heave the structure is destroyed due to a lack of earth pressure resistance.

He writes (Terzaghi, 1925, p. 375): „Falls nun das Gewicht an irgendeiner Stelle nicht hinreicht, um in der Erddruckzone senkrecht zu den Kraftlinien wirkenden Druck zu kompensieren, so tritt an dieser Stelle die als Zerrung des Sandes bezeichnete Erscheinung ein. Die Zerrung hat eine Zunahme des Porenvolumens zur Folge. ... d. h. es bildet sich am Ort der Umlagerung eine Zone erhöhter Durchlässigkeit. Die Stromlinien werden nach der Stelle verminderten

Strömungswiderstandes hin abgelenkt und die mit der Zusammendrängung der Stromlinien verbundene örtliche Zunahme der Strömungsgeschwindigkeit führt den Grundbruch herbei."¹

This description of the forces acting on the soil body during hydraulic heave and of the deformations and changes in the properties of the ground has lost none of its accuracy and relevance today, even if the names of the individual processes may be different today.

3 LINES OF FORCE

Terzaghi's concept of lines of force has not yet been sufficiently appreciated. In (Terzaghi, 1925, section 28h, p. 370) he describes in detail how the force field of dead weight and flow pressure interact and how the lines of force can be derived from this.

These lines of force, similar to streamlines, run through the ground and mark the direction of the greatest principal stress. "Die in einem beliebigen Punkt einer Kraftlinie an diese Linie gelegte Tangente gibt die Richtung der in diesem Punkt herrschenden Hauptspannung p an"² (Terzaghi, 1925, p. 372).

With this concept, Terzaghi was far ahead of his time. While today stress fields can be represented using numerical methods such as the FEM, Terzaghi's methodology remains a valuable didactic tool for intuitively understanding stress redistributions in the ground due to groundwater flow.

4 SURCHARGE FILTER

Terzaghi also developed the concept of the permeable, load-bearing filter load. He writes (Terzaghi, 1925, p. 376): "Die Auflast erfüllt jedoch nur dann ihren Zweck, wenn der Stromlinienverlauf durch die Anwesenheit der Last keine Änderung erfährt."³

This clearly distinguishes him from practitioners of the time, who often used surcharges as rigid, impermeable plates, which - as Terzaghi recognized - can even lead to an increase in the flow velocity in the outflow area next to the impermeable surcharge by compressing the streamlines.

His model tests showed impressively that a correctly designed surface filter with a permeable surcharge can significantly increase the critical head (Terzaghi, 1925, p. 377). This concept has found its way into modern regulations - but often without taking Terzaghi's underlying methodology fully into account.

This is also shown in the study by Odenwald and Herten (2008). If a surcharge filter is used, this initially results in a lower required embedment depth t of an underflowed wall in the ground. However, if the embedment depth of the wall in the soil on the outflow side is reduced further and further ($t \rightarrow 0$), both the soil weight and the flow force in the soil body, which is usually only considered above the base of the wall, approach zero, resulting in a required thickness d_F of the surcharge filter that also tends towards zero (Figure 2).

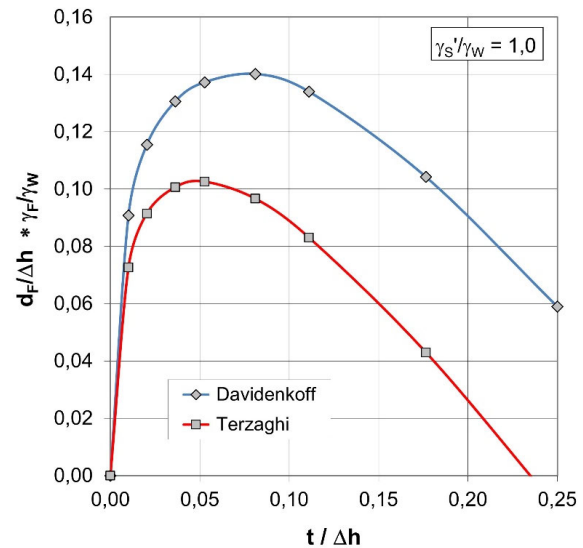


Figure 2. Required filter thickness d_F from the verification against hydraulic heave for the limit equilibrium according to Odenwald and Herten (2008)

Thus, for each underflowed wall with a surcharge filter on the outflow side, a sufficient mathematical safety against hydraulic heave could be proven if the embedment depth of the wall in the soil were reduced. However, it is obvious that a smaller integration of the underflowed wall into the ground cannot in reality lead to higher safety against failure due to hydraulic heave. A more realistic result is obtained if, as described by Terzaghi (1943), if the equilibrium is considered not only in a soil body extending to the base of the sheet pile wall, but also in a soil body extending into the ground below (Figure 3).

Terzaghi (1943) writes: 'With sufficient accuracy we can assume that the body of sand which is lifted by the water has the shape of a prism with a width $D/2$ and a horizontal base at some depth D_3 below the surface. The rise of the prism is resisted by the weight of the prism and by the friction along the vertical sides of the prism. At the instant of failure, the effective horizontal pressure on the sides of the prism and the corresponding frictional resistance are practically zero. Therefore, the prism rises as soon as the total water pressure on its base becomes equal to the sum of the weight of the prism, sand and water combined. The head h_p at which the body is lifted is the critical head.'

The elevation of the base of the body is determined by the condition that h_p should be a minimum because piping occurs as soon as the water is able to lift a prism of sand regardless of where its base is located. Figure 79b shows the base at an arbitrary depth D_3 . However, it can also be seen here that the safety would increase again with a very small embedment depth of the wall, although the pressure difference to be reduced also increases.

¹ "If the weight at any point is not sufficient to compensate for the pressure acting perpendicular to the lines of force in the earth pressure zone, the phenomenon known as distortion of the sand occurs at this point. The distortion results in an increase in pore volume. ... i.e. a zone of increased permeability is formed at the point of rearrangement. The streamlines are deflected towards the point of reduced flow resistance and the local increase in flow velocity

associated with the squeezing of the streamlines causes the ground failure." [Translation by the authors]

² "The tangent placed at any point of a line of force on this line indicates the direction of the principal stress p prevailing at this point" [Translation by the authors]

³ "However, the surcharge only fulfils its purpose if the streamline is not altered by the presence of the load." [Translation by the authors]

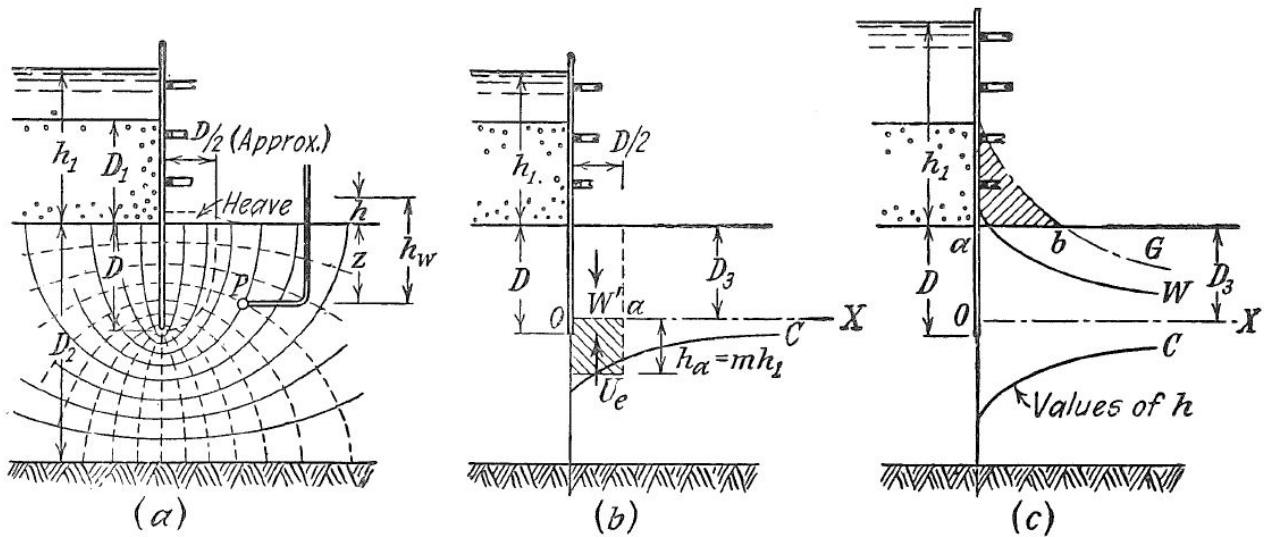


Figure 3. Graphical determination of safety against hydraulic heave according to Terzaghi (1943), Fig. 79

For this reason, Odenwald and Herten (2008) recommend not considering the mathematically decreasing surcharge at very small embedment depths (to the left of the maximum value for the required filter thickness, see Figure 4) when determining the required thickness of a surcharge filter.

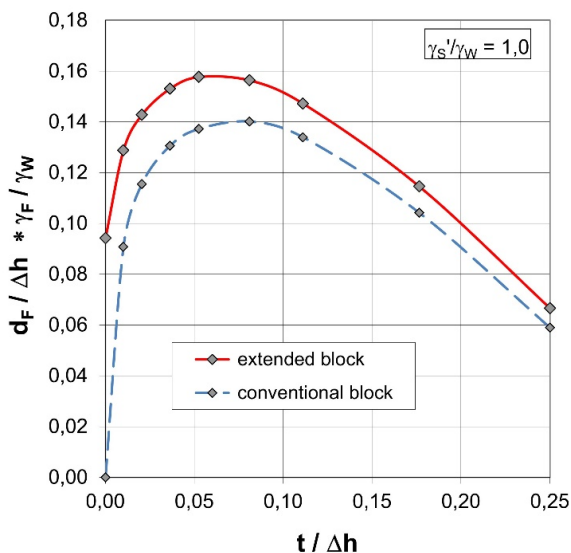


Figure 4. Required filter height d_F based on the verification of hydraulic heave at the improved relevant soil column for the equilibrium of forces according to Odenwald and Herten (2008)

5 REGRESSIVE EROSION

In his seminal book (Terzaghi, 1925), Terzaghi warns urgently of regressive erosion as the most dangerous failure mechanism. He writes (Terzaghi, 1925, p. 375): "Der Grundbruch erfolgt durch rückschreitende Erosion."⁴

He describes in detail how the sand first swells up on the valley side and is then washed out in a wide channel. A case study by Herten and Dornecker (2013) shows impressively that Terzaghi's warnings are still valid today. Erosion often occurs long before hydraulic heave, which underlines the need to verify

the highest priority to erosion safety when designing an earthwork against geohydraulic hazards.

As Terzaghi and Peck (1948) write: "Wherever seepage crosses a boundary from a finer to coarser material (note: here between ground and the surcharge filter) or emerges from a soil into an open space, such as a riverbank or a drillhole, the potential exists for some particles to migrate out of the finer material. The migration may have serious consequences. It may cause the clogging of packing or backfill around wells or of drains or it may result in the formation of erosion tunnels and sinkholes. Indeed, subsurface or internal erosion has been one of the most prevalent causes of catastrophic failure of earth and rockfill dams."

This means that even before the hydraulic heave described above can occur due to excessive flow forces, there is a risk of failure due to regressive erosion when the water begins to enter, even at low flow forces. Terzaghi and Peck (1948) go on to write: "However, if the removal of subsurface material is reliably prevented, the conditions for the validity of the theory of piping by heave are satisfied and the critical head can be computed. It is, moreover, very much greater than the critical head for subsurface erosion." Erosion can be prevented if the surcharge filter is dimensioned and carefully constructed in accordance with BAW code of practice MAK (2013). Hydraulic heave can be avoided by considering the application limits described by Odenwald and Herten (2008) when verifying against hydraulic heave according to Terzaghi.

6 EUROCODE

In the second generation of Eurocodes, the basic idea of Terzaghi can also be found in the verification method against hydraulic heave specified here. However, the safety verification is no longer carried out by comparing the weight of the soil to the ascending flow force, but on the basis of soil stresses, which means that the definition of the limit state must be redefined. Instead of a failure body according to Terzaghi with a width corresponding to half the embedment depth of the wall ($b = t/2$), Eurocode 7 (2014) prefers the consideration of a failure body on a stream line, as described by Davidenkoff (1970). The differentiation of the zones required by Terzaghi is thus

⁴ "Ground failure occurs by regressive erosion."
[Translation by the authors]

forgotten. However, FEM studies (Odenwald and Herten, 2008) confirm that Terzaghi's differentiated approach is still necessary in order to correctly capture the critical vertical flows, especially when the wall is very weakly integrated into the ground.

7 SUMMARY

100 years after Terzaghi's groundbreaking publication (Terzaghi, 1925), many of his findings on soil stresses and earth structures caused by flow forces are still valid. Moreover, his methodological rigor, his critical examination of simplifications and his ability to describe complex relationships with simple models remain a role model. Terzaghi succeeded in recognizing fundamental geotechnical relationships with the simplest means on the drawing board - with streamlines and lines of force - that are on a par even with today's calculations using numerical methods, when it comes to understanding the mechanisms.

8 REFERENCES

- Terzaghi, K. 1925. *Erdbaumechanik auf bodenphysikalischer Grundlage*, Abschnitt 28h: Die Beanspruchung des Baugrundes unterhalb von Stauwerken, Verlag Franz Deuticke, Leipzig und Wien,
- Terzaghi, K 1922. *Der Grundbruch an Stauwerken und seine Verhütung*, Forchheimer-Nummer der „Wasserkraft“, München
- Odenwald, B. and Herten, M. 2008. *Hydraulischer Grundbruch: neue Erkenntnisse*, Bautechnik 85, DOI: 10.1002/bate.200810044
- Terzaghi, K. 1943. *Theoretical Soil Mechanics*, Section C: Effect of seepage on the conditions for equilibrium in ideal sand, pp. 235-264, John Wiley & Sons, New York, DOI:10.1002/9780470172766
- Herten, M. & Dornecker, E. 2013. *Lessons learned from the disaster at Lippe canal bridge*, Seventh International Conference on Case Histories in Geotechnical Engineering
- Terzaghi, K. and Peck, R. 1948. *“Soil mechanics in engineering practice”*, John Wiley & Sons, New York
- MAK 2013. *Merkblatt Anwendung von Kornfiltern an Bundeswasserstraßen*, Bundesanstalt für Wasserbau
- Eurocode 7 2024: *Geotechnical design - Part 1: General rules*, FINAL DRAFT FprEN 1997-1
- Davidenkoff, R. 1970: *Unterläufigkeit von Stauwerken*, Wernerverlag Düsseldorf