Pressure spreading at soil water interfaces and its influence on soil structure design

H.-J. Köhler
Federal Waterways Engineering and Research Institute (BAW), Germany

Keywords: Canals, Design method, Embankments, Numerical modelling, Geotextile

ABSTRACT: : Soils under water are commonly considered to be saturated. In engineering practice the water itself is rated as being incompressible. Therefore the common approach of describing the behaviour of such saturated soils uses a two-phase model of solid soil particles and water filled voids. This two-phase model is not consistent with natural conditions and observations where microscopic air bubbles omnipresent in pore water are imbedded within the pore fluid in the soil skeleton. Those bubbles play a key role in soil behaviour, thus explaining soil failure and structure deformation. Boyle-Mariotte`s law can be used to examine the consequences of the pore water-air interaction. In soil mechanics this may be performed by applying a three-phase model, introducing the influence of such fine dispersed gas bubbles in soil structures below the piezometric line. So far applications have been mainly limited to unsaturated soils above the water level, where capillary suction zones may occur. The paper deals with possible failure conditions caused by changing water pressures and explains solutions that may be used in the design practice for safety assessments of navigable canals and coastal structures. The interaction between soil, water and protection structures, such as revetments is described. Solutions originating from numerical simulations are presented with special regard to structures including geosynthetics.

1 INTRODUCTION

The settling of Man in the river valleys of early Egypt and Mesopotamia was the reason for the survival of life in an area which was otherwise tormented by a hot dry climate. It was also the basis of what we today traditionally know about the early forms of this civilisation. Irrigation and drainage systems were made possible by learning to handle soil and water, which finally opened up new possibilities for water transport. It was the birth of canals and dykes.

In the second and third centuries BC the Nile ships were already able, by means of canals to circumnavigate the first and second cataracts as far up as the Nubian border. A former branch of the Nile was canalised. It extended up to the desert valley west of the Fayum river. This enabled the fields to be watered and the Province of Fayum developed into one of the richest areas of Egypt.

Numerous flood and river control systems in ancient China and India prove that early civilisation knew the art of handling the element of water. But not until 1000 AD did European canal builders start to step forward the direction of building dykes and artificial waterways to gain new land and also to act as a protection against flooding as we know well today in the Low Countries.

Soon canals were planned to serve as permanent traffic connections which were used by ships. This was made possible because the previous difficulty of having different levels of water at tidal changes and a usually lower lying inland waterway could be overcome by a system in which one water system could be divided from the other by a series of lifting gates. By this method continuous water transport was made possible and meant that laborious unloading and reloading times eventually became superfluous. The construction of a lock system meant that products could be transported far inland, propelling trade.

From the fifteenth century onwards many prosperous states were keen in constructing and ameliorating water transport facilities. Leonardo da Vinci and his contemporaries made several

schemes to regulate the North Italian rivers. In the Po valley many of these were actually built. In the area around Milan engineers developed a canal system which was connected together by permanent locks and pavis of locks enabling a flourishing ship traffic to develop.

An important contribution to the modernisation of water traffic as we know it today was the invention of hinged lock gates by Leonardo da Vinci through which the different water levels could be regulated by moving small sliding sealing plates attached to these gates. These canal and lock constructions helped to develop a high quality engineering standard being required in controlling the pressure interaction between soil and water.

The currents and waves created by navigation and water level changes during the actual locking processes round off the number of complicated loading factors which specialists in water constructions recognise as being inevitable in order to design, construct and maintain waterways. A great deal is still unknown about the interaction between water and soil.

Pressure changes applied on unsaturated submerged soils initiate volume changes of the embedded air bubbles inside the gas-water mixture. The immediate reaction of the air bubbles causes local transient flow (Köhler 1993, Köhler et al. 1996). This process is often hampered by low permeability thus creating delayed pore water pressure reaction. In some cases the hampered flow causes a delayed pore water pressure decrease which may be quoted as excess pore water pressure. According to Terzaghi`s principle the effective stress between the single soil particles will be reduced, leading to loss of friction. Soil structure changes may take place. Heaving and settling of soil segments and even interweaving soil movements (translation and rotation) may be induced especially in non-cohesive soils. This volume deformation is hampered in cohesive soils such as silt and clay with low permeability characteristics. The excess pore water pressure inside the pore volume is entrapped until the amount of pore water has been expelled out of the deforming soil. The decrease of external pressures acting on unsaturated submerged soils may induce fluidisation or pre-failure deformation processes. The delayed pore water pressure response can be described by the type of a consolidation equation attributed to Biot (1941).

2 EMBANKMENT PROTECTION MEASURES

Oscillating water level cause pressure changes in submerged soil which will endanger the safety of embankments. Where waves and rapid water draw down effects occur, sliding and soil movement is liable to take place. Embankments along waterways are especially liable to such loading, where rapid water level changes may cause damage to the embankment. The observed pressure dampening in the soil finds its explanation in the air content of the pore water, whereby excess pore water pressure responses in the potential sliding zones may induce sliding, preferable parallel to the embankment.

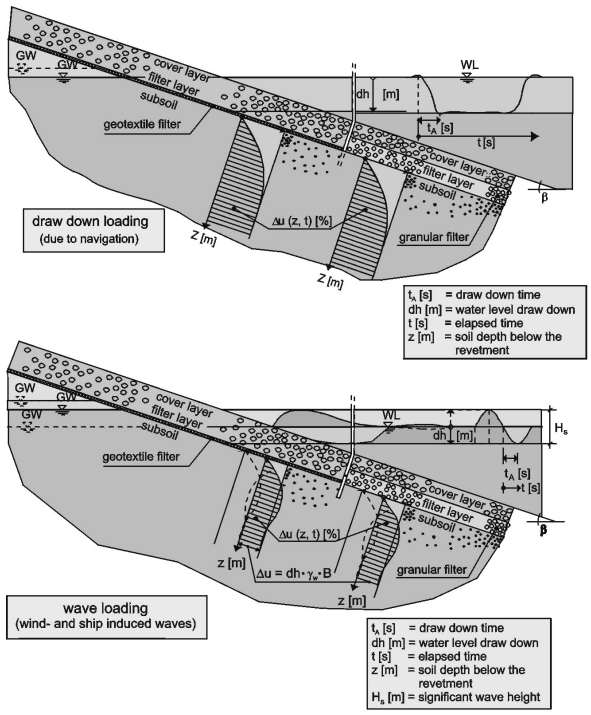

Figure 1. Excess pore water pressure induced by navigational draw down and waves caused by passing vessels and wind forces.

Figure 1 shows two examples of pressure changes caused by navigation and wind forces. A superimposition of the two pressure events can be expected. Pressure responses of this type do not only endanger embankments but they occur in the whole submerged soil and thus in the soil bed. Therefore these effects will naturally also occur in front of and behind of slanting or vertical retaining wall structures, leading to similar safety considerations as in the case of embankments loaded by draw down effects (Köhler, Haarer 1995).

Figure 2 shows the cross-section of a navigable canal bed and embankment, whereby the loading situation of a rapid draw down in the canal water level is shown as caused by passing vessels. An unsteady pore water pressure distribution in the subsoil will be initiated, overlapping the hydrostatic water pressure state at the final stage of the water level draw down at time t_A , acting over the depth z [m] perpendicular to the entry surface, owing to the rapid draw down value dh = z_A [m] on the unprotected bed as well as on the protected revetment embankment area. The course of the unsteady excess pore water pressure Δu(z,t) can be described by an exponential function with the parameters a(t) and b(t). Beyond that it is directly dependent on the draw down value dh = z_A [m] (Köhler 1997).

The pore water pressure parameter a(t) and b(t) describe specific load- and soil conditions, which may be evaluated clearly by laboratory tests and assumptions about the acting loads. Introducing these parameters into the exponential equation (1), the transient pore water pressure distribution Δu(z,t) may be described by:

$$\Delta u(z,t) = \gamma_w z_A (1 - a(t) e^{-b(t) z}) \qquad (1)$$

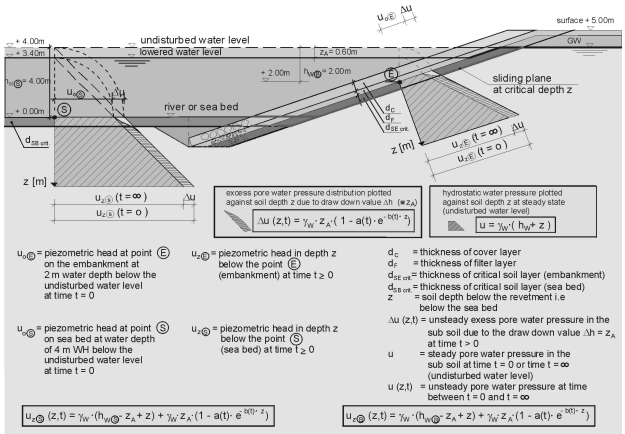

Figure 2. Water level draw down in a canal section and pore water pressure response

Essentially the parameter b(t) [1/m] determines the pressure course over the depth z [m] and is especially dependent on soil water permeability k [m/s] and the rapid draw down time t_A [s], in which the change of water level takes place, next to other here not explicitly mentioned soil properties. The parameter a(t) varies around the value of 1 and therefore has less influence on the temporal occurring pore water pressure distribution and is practically be negligible. Through the size of the occurring unsteady excess pore water pressure during the rapid draw down phase, the shear strength condition in a critical soil depth $d_{S\ crit.}$ [m] according to Coulomb's assumption will be endangered. This leads, if the weight of the bank protection and the effect of retaining forces on the toe of the slope is not large enough, to sliding of the embankment parallel to the surface within a critical soil layer $d_{S\ crit.}$ [m], caused by temporarily excess pore water pressure acting on it.

On the non-protected sea or river bed the excess pore water pressure Δu(z,t) effects the danger of boiling of a quasi-weightless, critical soil layer $d_{S\ crit}$ [m], which equals in the case of rapid water level changes the size of the draw down value z_A [m] and is even valid for bed materials consisting of gravely sand and sandy gravel. The water permeability k [m/s] of the soil under consideration here is decisive. The lower the k-value of the bed material the sooner the critical soil layer will be developed due to rapid draw down loading on the sea bed (Fig. 3)

The temporal development of the transient excess pore water distribution over the soil depth due to the event of the water level lowering or raising can be described by the exponential function (1), in which the parameters a(t) and b(t) change their values during the elapsed time t [s] for different soil characteristics. Similarly the direction and depth of the pressure spread depends on the type, size and duration time of the initiated underwater pressure changes. It is deeper and more widely spread the higher the water permeability of the soil and the less the proportion of gas-formed contents are to be found in the pore water medium. As well as soil compressibility modulus, the size of the water filled pore volume have direct influence on the development and spreading speed of the water pressure changes. The feed back of the pore water pressure on to the "grain to grain contact pressure" of the soil is also of essential importance. Deformation of the soil volume overlaps with the occurring pore water pressure, which will develop not only due to water level changes. Other outer loads such as vibrations (driving vibrations, oscillation etc.) or deformation (sliding, earth pressure adjustment etc.) as well as static loads and changing area- or point loading (disposal and foundation loads etc.) show similar pore water pressure characteristics, which are controlled in a similar way to the influencing parameters of the soil material and pore water mentioned previously.

Present conventional standard engineering design concepts assume that water carries itself through the pores in the soil structure, i.e. no settlement or lifting stress in the soil is caused - the classic soil mechanics uses the so-called neutral stress u. This can neither be accepted for rapid

water level changes nor for short term and varying load conditions for reasons which have been mentioned beforehand.

In reality the effects of load changes (water, solids and dynamic alternating loads) on submerged soils have a complex significance for the resulting interaction between pore water pressure and "grain to grain contact pressure". Inhomogeneous soils, caused by different soil layering, widely spread in nature, cause more than enough uncertainties for engineering judgement. Even more complications evolve from changing level conditions resulting from the change of ruling soil parameters such as modulus of soil compressibility and shear resistance of soil.

The pore water pressure spread is dependent mainly on the damping influence of the air present in the pore water and therefore also on the size and the distribution of its air volume in dependency on the surrounding total water pressure and on the surrounding temperature of the soil volume. In order to assess pore water pressure a quasi unsaturated soil condition below water level is assumed as test measurements have confirmed and will be shown in the following calculation for pore water pressure development and its influence on embankment and sea bed stability.

3 PORE WATER PRESSURE CHANGES DUE TO TRAVELLING WAVES

Water level liftings and lowerings induce counter directional changes in pore water pressures u(z,t) [kN/m²] inside the submerged subsoil. Transient pore water flow through the pore voids of the soil will be initiated, which may cause soil particle fluid flow transport at layered soil interfaces and especially at the interface between soil and water. Material transport and dangerous soil deformations may occur. The phenomena of retarded pore water pressures is connected to these loadings. For practical reasons a simplified numerical approach may be taken into consideration, using one dimensional and two dimensional numerical calculation methods with the solution principle of finite differences. They are sufficiently accurate as to calculate pressure changes in their temporal course effecting navigable water ways or wave-loaded embankments. To simulate the transient pore water pressure changes in the subsoil due to travelling draw down loading, various combinations of layered soil structures characterised by different soil parameters and different soil layer thicknesses may be taken into account, both in horizontal as well as in vertical directions. A typical result of such a calculation is demonstrated in the Figures 3 and 4, showing the pore water pressure changes in a homogenous subsoil stratum below canal bed, caused by a travelling wave. Along the horizontal section of a length of L = 20 [m] five different time steps of the travelling wave are shown. The velocity of the travelling wave is described by v = 0.1 [m/s]. The degree of saturation S [-] of the submerged subsoil has been chosen to S = 90 %. The marked numbers (1) to (5) describe the position of the wave, travelling over a homogenous subsoil stratum of the length L = 20 [m] (Fig. 3):

(1) L = 0.25 L, (2) L = 0.5 L, (3) L = 0.75 L, (4) L = 0.95 L and (5) L = 1.0 L

In the chosen case study the soil is influenced more or less up to a depth of more than 2.5 [m] below canal bed. The pressure decrease can clearly be seen. The depth of influence of the pore water pressure reduction becomes greater with increasing degrees of saturation S [-] of the soil. It is possible to describe the different layer horizonts in the soil, both in horizontal and vertical extension. The figures 3 and 4 show the results of a calculation for a load case of a travelling draw down loading on the water bed for different time transits, with which the trough travels through the 20 [m] length of the water bed section, as seen from the left hand side. The encircled numbers (1) - (5) describe the respective calculation results (see fig- 3).

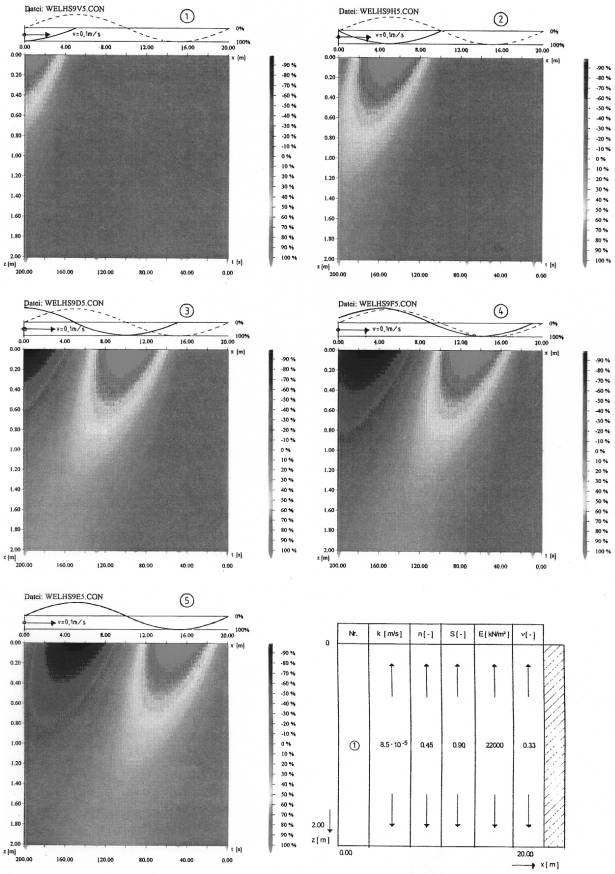

Figure 3. Calculated pore pressure response of a travelling wave

The main influences of soil parameter being most important for the pore water pressure spread are characterised by soil water permeability k [m/s], pore volume n [-], degree of saturation S [-],Young's modulus E [kN/m^2] and Poisson's ratio v [-].

Figure 3 shows the respective effecting pore water pressure distributions for each of the selected cross sections L [m] (1) to (5) plotted over the depth levels between z = 0 [m] to 2.0 [m].
The differential equation for a two dimensional calculation of the piezometer head φ [m] acting time dependent over the soil depth z [m] below sea- or canal bed, caused inside the submerged sub-soil by travelling waves at the water surface or draw down loading owing to navigational traffic, can simplified be written as

$$\frac{\partial}{\partial t}\varphi(x,z,t)=D(z,t)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)\varphi(x,z,t)+\varepsilon(z,t)\frac{\Delta}{\Delta t}\varphi(x,z,t) \qquad (2)$$

whereby a kind of retarded $\varphi_{ret}(x,z,t) = \varphi(x,z - v,t, t)$ has been taken into account of by the changing pressure decrease in vertical direction of the soil depth z [m] initiated by the rate of pressure changes due to the velocity of the travelling draw down and wave loading. This expression is the statement of the size in change of φ, if the previous development at the time (t-dt) at the local position of the soil element under observation (r(t) - v(x,z,t)dt) has been taken into consideration. This effect has to be introduced into the differential equation with the substantial derivation

$$\frac{\Delta}{\Delta t}\varphi(x,z,t)=\frac{\partial}{\partial t}\varphi(x,z,t)-v(x,z,t)\,\nabla\varphi(x,z,t) \qquad (3)$$

together with the diffusion constant D(z,t) as a function of soil depth z [m] and time t [s]:

$$D(z,t) = \frac{k(z,t)}{\rho\, g n(z,t) \cdot \beta'(z,t) + \rho\, g\, \alpha_E(z,t)} \tag{4}$$

and with parameters and variables:

- compressibility of the water-air-mixture

$$\beta'(z,t) = (\beta + \frac{1 - S(z,t)}{p_{atm} + \rho g h_w + \rho g z}) \tag{5}$$

- compressibilty of the soil for elastic behaviour

$$\alpha_E(z,t) = \frac{(1+\nu(z,t))\,(1-2\nu(z,t))}{E(z,t)\,(1-\nu(z,t))} \tag{6}$$

- volumetric strain of soil element

$$\varepsilon(z,t) = \frac{\alpha_E(z,t)}{n(z,t) \cdot \beta'(z,t) + \alpha_E(z,t)} \tag{7}$$

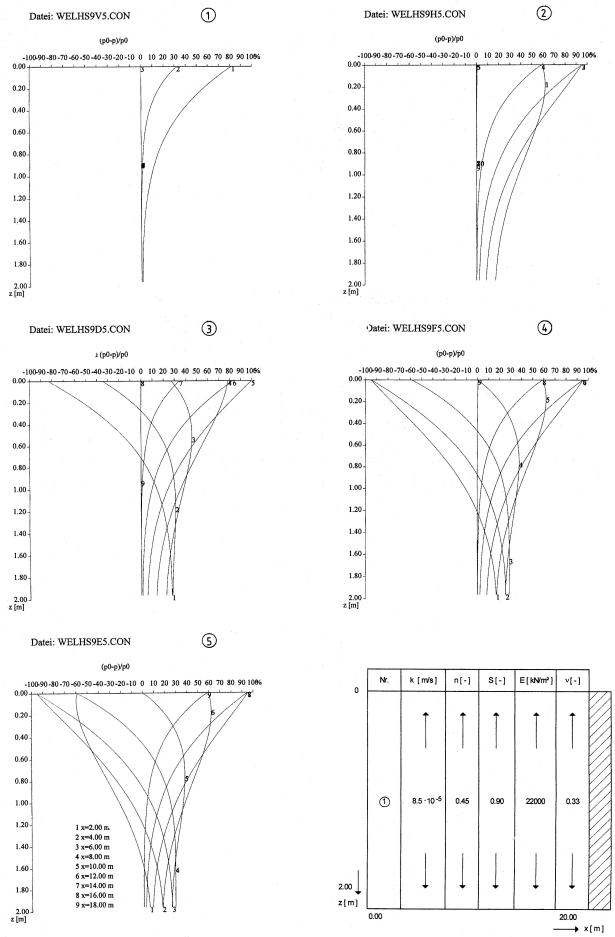

Figure 4. Vertical pressure distributions of the travelling wave

with the variables as a function of depth z [m] and time t [s]:

- of the soil

$E(z,t)$	[kN/m²]	= Youngs modulus
$\nu(z,t)$	[-]	=Poisson's ratio
$n(z,t)$	[-]	=pore volume
$S(z,t)$	[-]	=degree of saturation
$k(z,t)$	[m/s]	=water permeability
$\varepsilon(z,t)$	[-]	=volumetric strain in the soil
$E_S(z,t)$	[kN/m²]	= modulus of soil compressibility

- of the liquid

ρ	[kg/m^3]	=density of water
β	[m²/kN]	=compressibility of water
$\beta'(z,t)$	[m²/kN]	= compressibility of water-air-mixture

- of the environment

$p_{atm.}$ [kN/m²] = mean atmospheric pressure (101.3 [kN/m²])

ρgh [kN/m²] = hydrostatic water pressure above sea bed or embankment surface plane (function of water depth $h = h_w$)

ρgz [kN/m²] = hydrostatic water pressure below sea bed or embankment surface plane (function of soil depth z, counted perpendicular to entrance plane surface)

g [m/s²] = gravitational constant (9.81 [m/s²])

4 DESIGN CHART

The ruling pore water pressure parameter b(t) [1/m] can be read out of a specially established diagram (Fig. 5) assuming the simple case of a homogenous soil layer in dependency to the permeability k [m/s] and time t_A [s] of the actual water level lowering. Parameter b/t) [1/m] caused by a travelling draw down loading z_A [m] due to passing vessels has to be introduced into the equation (1) in order to calculate the excess pore water pressure $\Delta u(z,t)$ [kN/m²] acting in different soil depth levels z [m]. For simplification the parameter a(t) can be taken as a = 1. The diagram may be used for dimensioning purposes of revetments on inland navigational canals or may be used for other draw down loadings like flooding high crest or tidal situations.

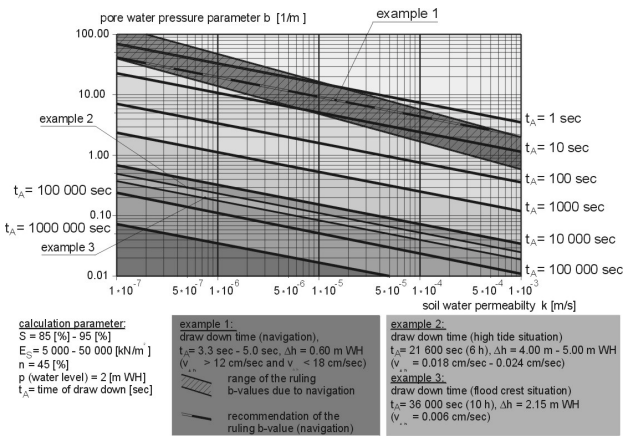

Figure 5. Pore water pressure parameter b(t) - design chart

Figure 5 shows an even further going interpretation for the ruling pore water pressure parameter b(t) dependent on the draw down time t_A [s] when the deepest point of water level lowering is reached. Example 1 (ship induced draw down) describes the dependency of the pore water pressure parameter b(t) on the water permeability k [m/s] of the soil for a draw down time t_A = 3.3 to 5.0 secs (draw down velocities between v_{zA} > 12 [cm/sec] and v_{zA} < 18 [cm/sec]) (Bezuijen, Köhler 1996).

Example 2 represents a much slower water level draw down situation, as in the course of a tidal change of 4 to 5 [m WH], with a draw down time of t_A = 6 hours (draw down velocity of v_{zA} = 0.018 to 0.024 [cm/sec]), but with a similar size as can for example be met with case 3 describing a flood crest situation. The diagram relates itself to the design parameters of the subsoil, degree of saturation S = 85 - 95 [%], modulus of soil compressibility E_s = 5.000 - 50.000 [kN/m^2], pore volume n = 45 [%] and an average depth over the water bed of about 2 [m] water height. The pore water pressure course to be estimated for each separate draw down situation is, corresponding to the draw down time t_A [s], dependent on the water permeability k [m/s] of the subsoil. Using the exponential equation (1), the unsteady pore water pressure Δu(z,t) can be calculated with the ruling pore water pressure parameter b(t):

$$\Delta u(z,t)\ [\mathrm{kN/m^2}] = \gamma_w \cdot dh \cdot B(z,t)$$

$$\text{where} \qquad B(z,t) = (1 - a(t) \cdot e^{-b(t) \cdot z}) \qquad (8)$$

may be quoted as the transfer function controlling the pressure spreading process.

In diagram Figure 5 the ruling pore water pressure parameter b(t) [1/m] has been plotted over the water permeability k [m/s] of the subsoil in dependency to the acting draw time t_A [s]. The transient pore water pressure state may easily be calculated by introducing this pore water pressure parameter into the equation for the determination of the prevailing excess pore water pressure Δu(z,t) [kN/m²] at the time of which the draw down value dh = z_A [m] reaches its decisive size at the time t_A [s]. In the example of loading case due to navigation a draw down value of dh = z_A = 0.60 [m WH] may be considered as design parameter for revetment construction at inland navigational canals, where draw down velocities between 12 [cm/s] and 18 [cm/s] may occur. Draw down and ship induced wave loadings will be covered by these design values. The range of the ruling b-values is very much influenced by the prevailing stiffness of the soil. The diagram of Figure 5 takes this influence into consideration by reducing the b-values with decreasing soil water permeability k [m/s] (see white black dotted line). Silty or even clayey soils with rather small permeability values k [m/s] may easily deform with increasing and decreasing loadings, which will be expressed by the soil compressibility modulus E_s [kN/m²]. In the case of a decreasing pressure load an extension of the soil pore volume (dilatation) takes place. With increasing pore volume, transient excess pore water pressure will also be reduced. Therefore b-values will also decrease with small water permeability values k [m/s] of the soil, because the ruling stiffness of such soils will also decrease. For simplification reasons this decreasing influence of small soil stiffness is also taken into account of for much greater draw down time values t_A [s] (Fig. 5), which may be of importance for flooding and tidal situations.

Lifting and settling of the soil volume ("breathing of the soil") may occur with oscillating water level changes, which will also reduce the acting b-values. This effect may be calculated and can be investigated by laboratory and field measurements.

5 LOADING CAUSED BY FLOODING AND BAROMETRIC PRESSURE FLUCTUATION

Flooding and barometric pressure fluctuations may also influence the stability of embankments and retaining walls. High water dykes may be endangered not only during the raising water level where seepage takes place from the water side to the down stream side of the dyke, but sliding may also take place due to the fact that the saturation of the dam body during high flood situations may cause

sliding on the water side due to draw down effects, resulting in transient excess pore water pressure. Figure 6 shows a schematic course of such a flood wave and a rapid draw down value dh [m] combined with draw down velocities v_{zA} [m] after the saturation phase, which is dependent only on the endurance of the flood water situation.

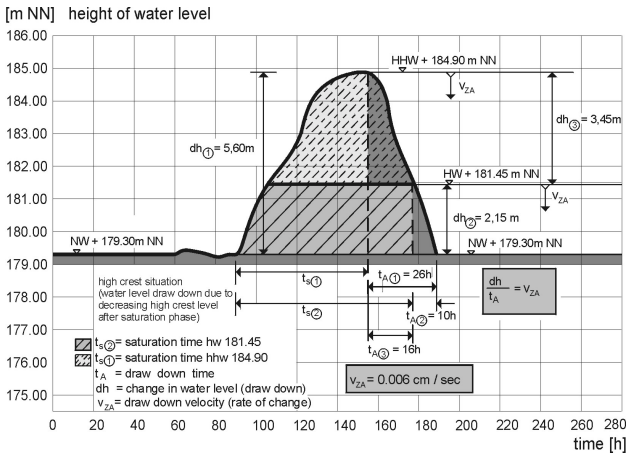

Figure 6. Raising and draining flood water situations with saturation and lowering phases

Using the decisive rapid draw down times t_A [s] and the predominate water permeability values k [m/s] of the dam body and the subsoil material, the pore water pressure parameter b(t) may be determined from Figure 5, which describes the decisive excess pore water pressure $\Delta u(z,t)$ [kN/m^2] for the transient state. The pore water pressure parameter a(t) may be chosen for simplification reasons to a(t) = 1.

The special case of a transient pore water pressure discharge arises out of the previous reflections on the three-phase system of submerged soils for daily barometric pressure fluctuations $dh_{atm.}$ [m]. Assuming a mean barometric pressure situation of 1013 [hPa], which in the case of an anticyclone can reach an atmospheric pressure of $p_{atm.}$ = 1063 [hPa] and in the case of a depression (storm) a value of $p_{atm.}$ = 963 [hPa] may develop, the effect on the sliding potential in the shear zone of the submerged subsoil may not be overseen. In soils with water permeability values of $k < 1x10^{-7}$ [m/s] (or even greater) and taking normal barometric pressure fluctuations into consideration, excess pore water reactions may well occur, which could be relevant for stability assessments. The effects of this excess pore water pressure caused by barometric pressure fluctuations may occur on all potential shearing zones in soils below ground water level (Schulze, Köhler 1999) and can therefore not remain without being considered as an influencing factor in all cases of unstable constructions. These reflections on excess pore water pressure caused by barometric pressure fluctuations have their special importance for all unstable slopes and embankments in low permeable soils. Sliding may easily be induced, which up till now has often been explained solely by decisive reductions of actual shearing resistance of the soil in question.

6 REVETMENT STRUCTURE INCLUDING GEOSYNTHETICS AND DRAINING FACILITIES

In order to increase revetment stability it is advised to counteract the transient excess pore water pressure due to draw down or wave loading by an adequate top load. Instead of increasing the weight of the revetment by greater layer thickness, draining systems seem to be an effective counter measure. For this purpose the use of draining pipes with a length of about up to two meters would be appropriate, when the distance of the drain points, positioned on the embankments, would

not exceed more than the shown distances of a or b = 1,50 m (upper part of Figure 7). The lower part of Figure 7 suggests a layered geotextile structure combined with geotextile cover. For the suggested revetment structures it can be demonstrated, that excess pore water pressure reductions will increase embankment stability. The results of a simulated draw down loading of dh = 0.80 m due to navigation

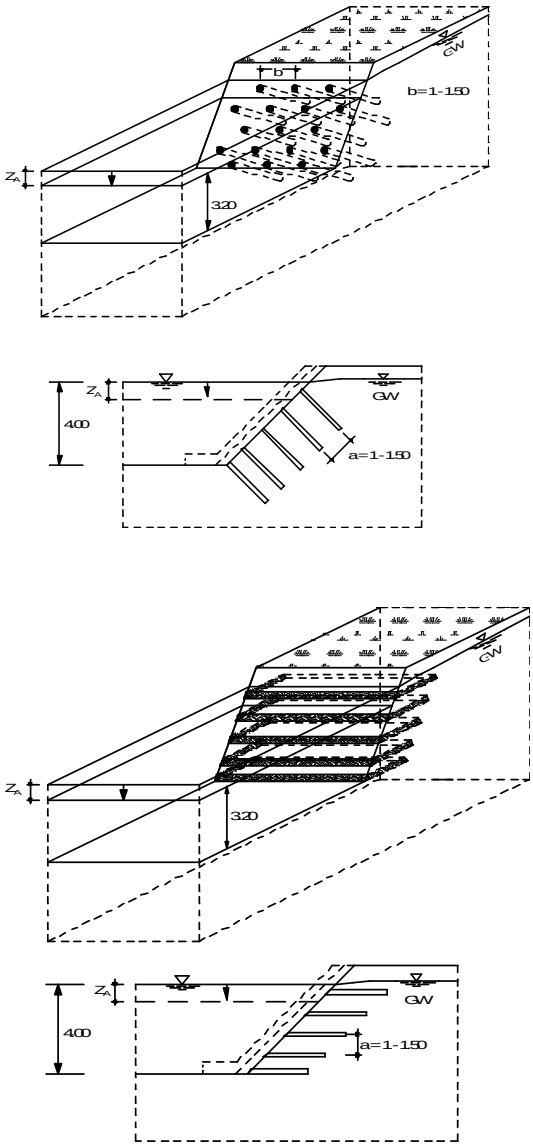

Figure 7. Revetment using geosynthetics and draining facilities,

case a – drain pipes connected with geotextile filter layer (upper part), and case b – horizontal geotextile layers (lower part), dimensions in cm

are plotted in Figure 8, which have been calculated with a tube or horizontal geotextile length of not more then 60 cm. The upper part of Figure 8 shows the calculation result of pore pressure response with the suggested draining tubes of 60 cm length. In comparison to these calculation the pore pressure response in the subsoil below the revetment without additional draining structures are

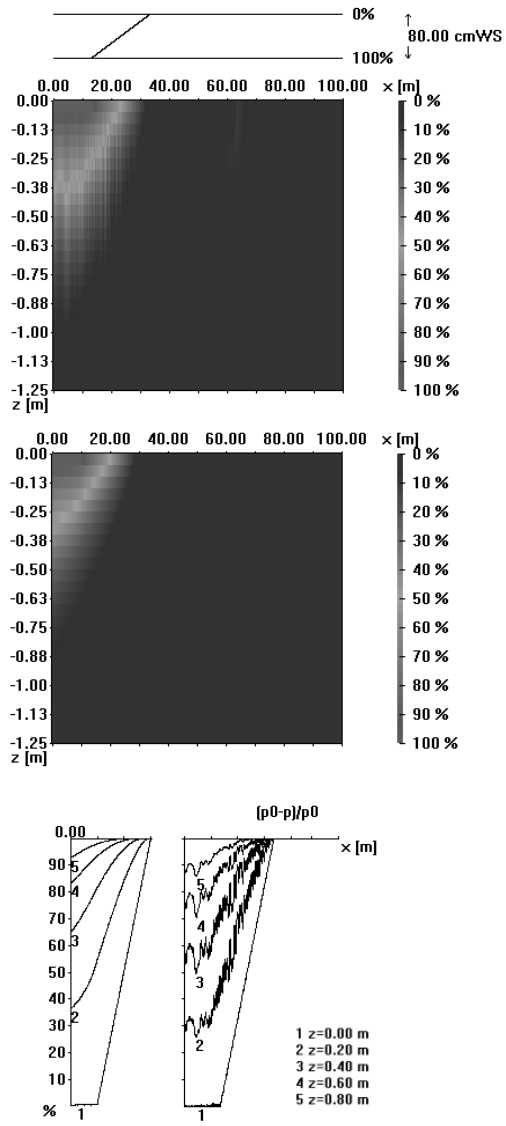

Fig. 8 Calculated pore water pressure due to draw down loading of dh = 0.80 m

shown in he middle part of Figure 8. The draining function of these pipes can clearly be seen in the lower part of Figure 8. Already in the depth level of 20 cm below the revetment cover layer the de crease in excess pore water pressure can be noticed. With these results a much more effective pressure release can be expected, when the draining length of the geotextile structures is increased.

7 CONCLUSION

The results of the investigations at issue on retarded pore water pressure in submerged soils have clearly shown, that already small quantities of natural air content in the pore water have influence on failure conditions, which should not be neglected in the design of water loaded structures. It is a strong recommendation to consider such loading situations in future design.

REFERENCES

Bezuijen, A., Köhler, H.-J. 1996. Filter- and revetment design of water imposed embankments induced by wave and draw down loadings, *Proceedings of First European Geosynthetics Conf. EuroGeo1, Maastricht, the Netherlands, 30th Sept .- 2nd Oct. 1996*: 1007 – 1023, Rotterdam: A. A. Balkema

Köhler, H.-J. 1993. The influence of hydraulic head and hydraulic gradient on the filtration process, *Proceed. of the First Intern. Conf. Geofilters'92 Filters in Geotechnical and Hydraulic Engineering*: 225 – 240, Rotterdam: A. A. Balkema

Köhler, H.-J., Haarer, R. 1995. Development of excess pore water pressure in over-consolidated clay, induced by hydraulic head changes and its effect on sheet pile wall stability of a navigable lock, *Proceed. of the 4th Intern. Symposium Field Measurements in Geomechanics, Bergamo, FMGM95:* 519 – 526, Padua: SGE.

Köhler, H.-J., Haussecker, H., Jähne, B. 1996. Detection of particle movements at soil interfaces due to changing hydraulic load conditions, localised by image processing technique, *Proceed. of the 2end Intern.Geofilters'96 (eds. Lafleur, J., Rollin, A.,L.):* 215 – 226, Montreal: Bitech Richmond BC.

Köhler, H.-J. 1997. Porenwasserdruckausbreitung im Boden, Messver-fahren und Berechnungsansätze, *Mitt.-Blatt BAW (No.75):* 95 - 108

Schulze, R., Köhler, H.-J. 1999. Landslides in over-consolidated clay – geotechnical measurements and calculations, *Proceedings of the 12th ECSM-Conference Amsterdam (eds. Barends et al.) (Volume 1):* 601 – 608, Rotterdam: A. A. Balkema