ABRUPT WATER PRESSURE VARIATIONS IN PERMEABLE SOILS

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Received July 15, 1986
Presented by Prof. Dr. M. Kozák

Abstract

It is the condition of up-to-date dimensioning of hydraulic structures to take into consideration all effects with their real value. That is why the investigation must be expanded to the hydrodynamical phenomena which occur due to an abrupt pressure head variation. Formulae were derived to determine the transition time of pressure variations and the velocity of a hydraulic bore. The formulae were verified by experiments. It can be established that in soils with a different permeability coefficient aperiodical pressure variation forms due to abrupt pressure variation. This abrupt variation does not cause a dangerous surplus dynamical load. One could also see, that the velocity of a hydraulic bore is about one hundredth of the velocity in systems, filled with pure water. The hydraulic bore does not cause a phenomenon or load, similar to those caused by a water hammer.

Introduction

During the operation of barrages the hydraulic bores, undulation of the surface, undular hydraulic jump, etc. causes rapid and sometimes periodical variation in pressure difference between head- and tailwater. If these phenomena caused a hydraulic bore in the zone of seepage, and if it could spread without damping, it might induce a pressure fluctuation corresponding to the total height and to the period of the wave at the foundation slab of the structure. This effect might act on the structure as a fatigue load, in some cases vibration may form and the soil structure might be damaged.

We considered it necessary to realize theoretical studies and laboratory measurements to determine the character and the time-process of an abrupt water pressure variation in soils with different permeability coefficients, and to determine the velocity of the hydraulic bore. The purpose of the laboratory measurements is to verify the formulae gained by theoretical derivations, and to gain experience, useful in practice.

Theoretical considerations, laboratory measurements

Theoretical Studies

The phenomenon was approached by a theoretical model to clarify the connection between the abrupt variation of tailwater and the variation of pressure in time [1]. During the investigations it was supposed, that the zone of seepage has fixed boundaries, the fluid and the soil grains are incompressible. The entire variation of pressure is compensated by the inertia of the water in the pores, and by some resistance-like parameters. The transition time of the velocity variation due to abrupt pressure variation is given by the following formula:

$$t = \frac{k}{g} \ln \left(\frac{1}{1 - \frac{v}{v_0}} \right) \tag{1}$$

where

k: coefficient of permeability of the permeable soil;
g: gravity acceleration;
v_0: initial velocity of the seepage
v: the transformed velocity of the seepage
t: time needed for the development of the transformed velocity.

Figure 1 shows the connection between the parameters of formula (1)

In reality the seepage zone is bounded by impermeable layers with a modulus of elasticity. That is why it is necessary to transform formula (1) in such a way, that the constants of the examined soils having different permeability coefficients and the effect of the elasticity of the waterproof boundaries are taken into consideration in a coefficient β. The value of β must be determined in case of a given soil and confining layers by experiments.

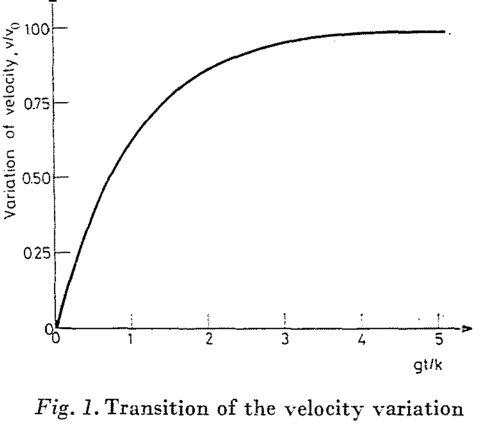

Fig. 1. Transition of the velocity variation

Replacing the variation of velocity (v/v_0) by the variation of pressure, which is proportional to v/v_0 (in the same soil and same system linearly proportional) the next formula can be derived from eq. (1):

$$\frac{\Delta h}{H} = 1 - \exp\left(-\frac{1}{\beta}t\right) \tag{2}$$

where besides the terms of (1) Δh is the abrupt, H is the total pressure variation.

To study the velocity of a hydraulic bore due to abrupt pressure variation we supposed a theoretical model, where the seepage zone with a circular cross-section is bounded by an elastic, waterproof layer with a given thickness [2]. A continuity and a momentum equation can be defined, where the variation of velocity, pressure and volume between two examined cross-section of the tube-model is taken into account. The derivation gives the velocity of a hydraulic bore (W):

$$W = \sqrt{\frac{1}{\varrho}\frac{1}{\dfrac{n_0}{\alpha E_v} + \dfrac{D}{e}\dfrac{1}{E_h}}} \tag{3}$$

where

- ϱ: density of water,
- n_0: pore space of the permeable layer;
- α: a factor, which takes into account the effect of the air and gas bubbles in the soil, $\alpha \sim 1$;
- E_v: modulus of elasticity of water
- D: diameter of the elastic boundary;
- e: thickness of the elastic boundary;
- E_h: modulus of elasticity of the soil bounding the seepage zone.

Equation (3) can be derived in a way that factor α, which takes into account the characteristics of soil, or a given system forming a permeable-impermeable layer is replaced by a constant of the system, which can be determined either by experiments of by field measurements. So equation (3) becomes:

$$W = \zeta \sqrt{\frac{1}{\varrho}\frac{1}{\dfrac{n_0}{E_v} + \dfrac{D}{e}\dfrac{1}{E_h}}} \tag{4}$$

Laboratory Measurements

The basic idea of the method of laboratory measurements is as follows. With the help of an equipment shown in Fig. 2, by suitably setting both the upper and lower weir crests, a hydraulic gradient and velocity corresponding to the phenomenon of seepage forms both in case of water flow through the total cross-section, and in case of flow through a permeable, granular soil, which was filled into the tube. Between two given points of the tube, in a distance l, we measured the time process of the abrupt pressure variation and the displacement (or the identity) of the hydraulic bore in time both in case of a tube filled with water and filled with soil forming a quasi two — phase water — soil system. Comparing the results of the measurements, the variation, depending on the permeability coefficient of different soils, can be determined.

If there is no deviation between the characteristics of the pressure variation, between the duration of the process and the velocity of the hydraulic

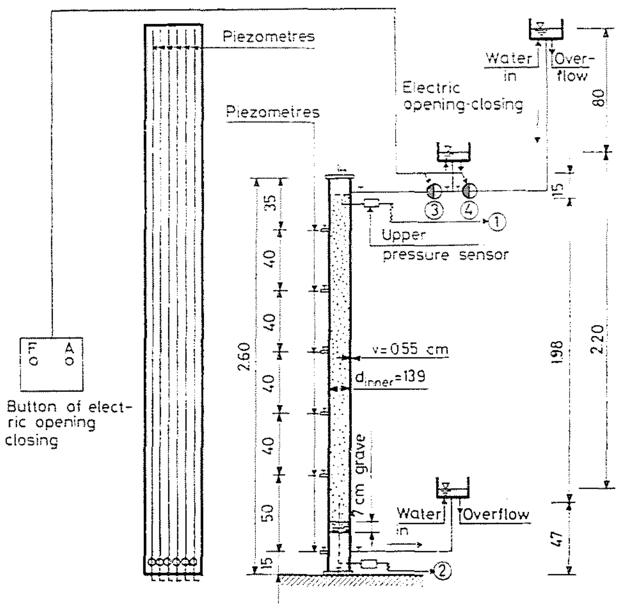

Fig. 2. Equipment for the experiments

bore in water and in different quasi two — phase systems formed by different soils, then these do not depend on the one — or two — phase characteristics of the system, otherwise a dependence must be supposed.

The length of the tube for the comparative measurements was 2.6 m, the diameter was 13.9 cm, the wall thickness 5.5 mm, and the modulus of elasticity was 2.10 MPa. The upper end of the tube was closed by a plate, which could be fixed by a fastening. In the middle of this plate there is a gas priming valve. At the upper end of the tube there is a weir, stabilizing the pressure of the water coming from the filling pipe. The filling pipe has two branches. In both branches of the pipe an electrically operated valve was fitted in, the end of the pipe was joined to the pressure stabilizing weir placed at different heights. The simultaneous opening-closing of the valve could be achieved by an electrically operated magnetic valve. If abrupt gradient variations must be produced, then pressing the operation button adjusts the two valves simultaneously but in different directions so, that the weir with a higher or lower pressure is in connection with the system.

The distance between the two pressure detectors is 2 m along the axis of the tube. The pressure detector pipes, each with a diameter of 5 mm, are connected to a PHILIPS pressure transformer, outside of the tube. The pressure transformer is a total bridge, compensating variations of temperature during the measurements. The two pressure transformers were jointed to a METRA dual channel amplifier. Further amplification was achieved by a DISA equipment.

The signal proportional to the pressure was registered by an 8-channel ultraviolet recording instrument. With this equipment one can adjust the velocity of the recording chart to 0.3; 1 mm $\times 1000$; $\times 100$; $\times 10$ mm/s, and is thus suitable to register abrupt transient and retarded processes reliably.

To decide reliability of the measured results, control measurements were performed. For these measurements the equipment was filled with pure water because the high velocity of the pressure wave and the homogeneity well demonstrate the behaviour of the system.

The size and the time process of the pressure fluctuation developing in the tube filled with pure water can be followed reliably with an accuracy of 0.01 s. By reason of this it could be concluded, that the equipment is suitable for the perception of pressure variation processes which are slower than the process in pure water.

The measurement of the velocity of a hydraulic bore forming in the seepage zone is made possible because the recording equipment, joined to the upper and lower pressure indicator, indicated the hydraulic bore at different times in the soil, in contradiction to the measurements in pure water, which means, that the duration of propagation of the pressure wave would be measured.

Measurement Results

In connection with the analysis of the results gained by the measurements, the classification of the system must be considered from the point of view of the pressure fluctuation caused by an abrupt pressure variation.

From the point of view of the physical basis of a hydraulic bore produced by abrupt pressure variation, and the constants of the experimental system, it can be established, that the phenomenon proceeding in the system can be described by the differential equation of the damped oscillation of single degree of freedom:

$$m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + kx = 0 \quad (5)$$

This equation is valid for all the systems, where the direction of the movement of the mass m corresponds to axis x, and the reserved energy of the system decreases due to internal or external friction, or perhaps due to a damper fitted in the system. Besides the formerly determined terms, in equation (5) k means the restoring constant, or corresponding to this the force needed for a unit deformation, c is a damping factor proportional to the velocity.

Connecting the maximum amplitudes of the pressure wave, a curve can be drawn with the formula, as follows:

$$x_{max} = 1 - \exp\left(-\frac{c}{2m} t\right) \quad (6)$$

This curve describes the effects in connection with the produced pressure variations in a given system. If there is a damper fitted in the system, which changes the parameters of equation (6) in a way that they will be above the curve of eq. (6), characteristic for a former system, the oscillation still remains damped, but the amplitude decreases. If the damper (e.g. friction) causes a damping, that the curve is below the one computed by eq. (6), the system turns overdamped and movements form, that are characteristic for over-damped systems. In this case the movement turns aperiodic, and reaches the equilibrium condition without any fluctuation.

By analyzing the shape of the curves in question, when the system is filled with water or soil, basic differences can be observed. When the system was filled with water, oscillations were observed, which characterize damped systems (Fig. 3). But when the system was filled with soil, an amplitude could not be observed, and the pressure reached the permanent pressure without fluctuation, characteristic of aperiodical systems (Fig. 4). Equation (2) and the formulae, expressed by a differential equation of first order, describe the process, which can be determined by experimental diagrams. So it may be concluded, that the duration of pressure variation in granular soils due to abrupt pressure variation is critically, characterizing damped systems or perhaps follows the laws to a greater extent, and the transition of velocity and pressure variation can be determined by eq. (1), or in case of an elastic boundary by eq. (2).

A constant β factor can be determined for the pressure curves of different soil classes, having the same hydraulic and experimental conditions. With the aid of β an exponential curve can be drawn. Plotting the data gained by the experiments on this curve, one can see, that the value of β can be considered as constant, and the points determined by the measured values

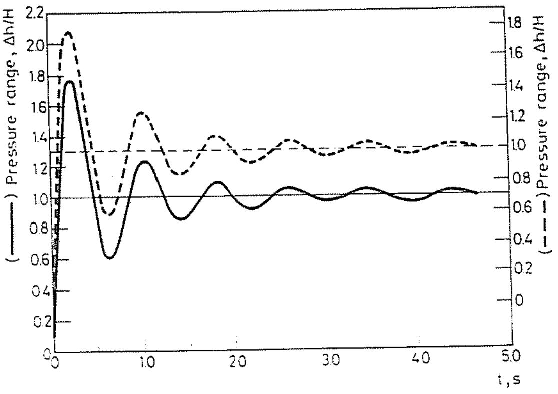

Fig. 3. Time process of pressure variation in case of a system filled by water

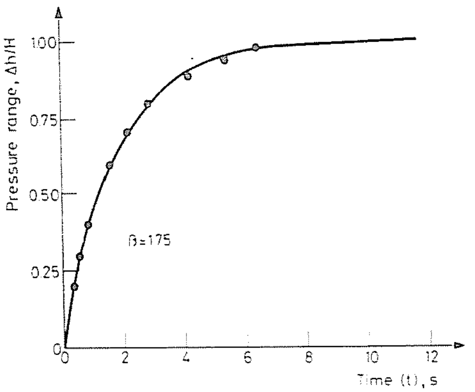

Fig. 4. Transition of the pressure variation in case of $\beta = 1.75$

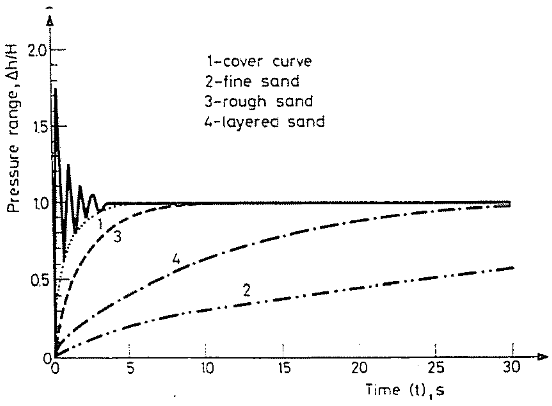

Fig. 5. Transition of pressure variation in case of a system filled with water and filled with soil with different permeability coefficients

of the pressure and time are placed either on, or with a small deviation, around the curve (Fig. 4).

In Figure 5 one can see the curves of the abrupt pressure variation in the opposite direction of the flow. Studying the pressure conditions in water or in different types of soil it can be seen that the seepage zone filled with sand has a strong pressure equalizing effect. In the seepage zone pressure fluctuation was not observed and the curves were in the zone of overdamping. The range of damping in soils with a smaller coefficient k is greater than in soils with a greater permeability coefficient. In the forming of a damping effect the friction resistance, the reflection processes due to the variation of the size of pores, the elasticity of water in the soil, etc., have a great importance. The aperiodical pressure variations do not produce a dangerous dynamical surplus load.

We also studied the case, when there is a finer cover layer above the rougher permeable soil. Its effect on the fluctuation was examined. That is why the upper 1/6 of the rough sand (3) was removed and replaced by a layer of fine sand (2). The result of the experiment, the curve describing the pressure variation, is continuous, there is no fluctuation and it is between the curves of rough (3) and fine (2) sand (Fig. 5). The slowing down effect of the fine upper layer is strong, and it is important in the damping of wave fluctuation. On the basis of the examinations one can conclude that if there is a sedimentation of silt at the upper layer of alluvial soils, the oscillations due to abrupt pressure variation is decreasing.

The propagation velocity of a hydraulic bore can be determined by equation (4), if the characteristics of the permeable and impermeable zones and the modulus of elasticity of water is known. But we do not know the influence of the other factors (e.g. gas, air, elastic boundary) on the velocity of the hydraulic bore.

A rigid, but elastically bounded soil prism was applied for the more accurate investigation of the phenomenon. The equipment is the same as the one in Fig. 2. Being aware of the geometrical and the physical characteristics of the tube material we could determine the velocity of the hydraulic bore if the system was filled with pure water. Filling the system with different types of soil and measuring the duration of hydraulic bore propagation, the deviation of velocity compared to pure water can be calculated. At abrupt closing the following results were gained for the factor ζ:

rough sand	$\zeta = 0.037$
medium sand	$\zeta = 0.023$
fine sand	$\zeta = 0.007$

The average propagation velocity of the hydraulic bore is as follows:

water	$W = 273.20$ m/s
rough sand	$W = 10.25$ m/s

medium sand $W = 6.41$ m/s
fine sand $W = 1.92$ m/s

From the results of the measurements it can be seen that the finer the sand the lower the velocity, is compared to the original velocity of the hydraulic bore.

Considering the results from the point of practice, it can be concluded that even with a nearly identical pore space a great deviation in velocity can be observed. The reason is that the permeability coefficient of the boundary layers, the series of widening and tightenings due to the grain shapes, the adsorbed air and gases, etc. can change the modulus of elasticity. Besides, all the two-phase systems must be divided, which on the one hand originate in geological ages, and on the other hand were formerly three-phase (e.g. a decline of water tables was applied). In the latter soils one can expect, that the adsorbed air, or that remained in the pores decreases the velocity of a hydraulic bore. Though the velocity of a hydraulic bore in confined permeable layer is less than in pure water, it is high enough for the pressure variation, occurring in practice, to propagate fast. It can be also established, that the hydraulic bore due to an abrupt pressure variation does not cause a phenomenon or a load like a water hammer.

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