Long-term observation of horizontal displacements of a weir

Surveillance longtemps des déplacements horizontaux d'un barrage mobile

H. SCHULZ, Dr.-Ing., Bundesanstalt für Wasserbau, Karlsruhe, FRG

SYNOPSIS Measurements at the weir of Iffezheim at the river Rhein showed seasonal oscillating displacements. The paper describes the employed measuring system and explains the mechanism of movements of the measuring points mounted beneath the foundation slab and the mathematical background for analysing the observed behavior.

INTRODUCTION

North of Straßburg the two barrages of Gambsheim and of Iffezheim near Baden-Baden were built in order to prevent the increasing bottom erosion of the river Rhein and the subsequent lowering of the ground water table. To get a sufficient factor of safety against sliding of the weir of the barrage of Iffezheim, a full embedded cantilever wall (see figures 1 and 2) was constructed at the downstream end of the building.

In connection with dimensioning this cantilever wall some predictions had to be made concerning the displacements of the weir that could occur due to the increasing water level behind the barrage.

It was decided to measure the horizontal displacements of the weir in order to check up the values which were assumed for dimensioning the downstream cantilever wall and to get a basis for design of further barrages.

THE BUILDING AND THE MEASURING DEVICES

The barrage provides a water level difference of 11 meters and consists of a weir at the left river bank, a dam, a power house and two locks at the right river bank.

The weir itself has six openings, each 20 m of width, built symmetrically to the axis of each pillar (figures 1 and 2). For further details see Martens and Klose, 1975.

Each pillar and one half of each of the openings at the left and right hand side of the pillar together form one block of the weir.

Because of lack of time between the date of decision to perform measurements and the necessary beginning of activities for instrumentation a rather unpretentious system was chosen.

As shown in figure 1 and 2 three measuring frames were installed at the bottom of block 1. Each frame consisted of two rods of 3.5 m length, driven into the ground beneath the foundation base, inclined at 15° against this base and directed upstream and downstream. So the influence of seasonal changes of temperature on the measurements of horizontal displacements was eliminated and the movements of the weir were measured against a horizontal plane 0.80 m below the foundation level.

The displacements itself were measured with transducers of the inductive type with an accuracy of 0,1 %, which were mounted within concrete casings at the bottom of the stilling basin slab (figure 3).

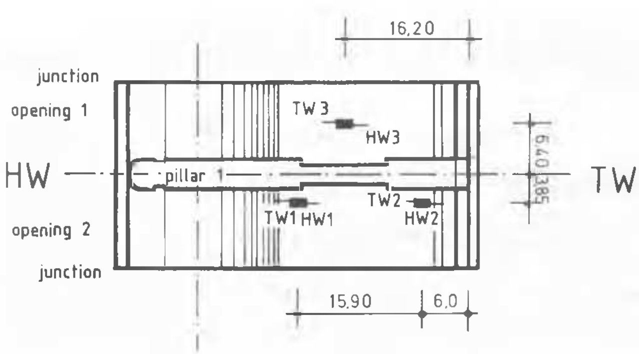

Fig. 1 Ground-plan of weir of Iffezheim with the position of the measuring points

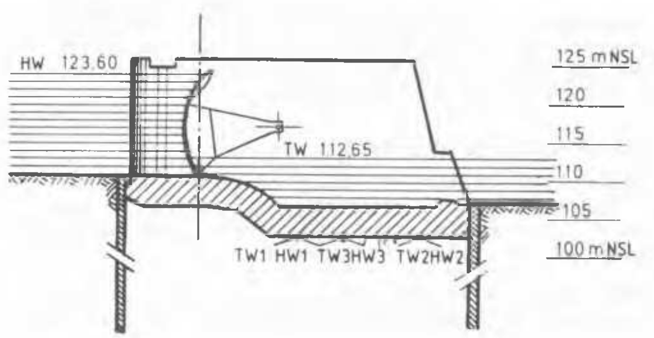

Fig. 2 Cross-section of weir with measuring points

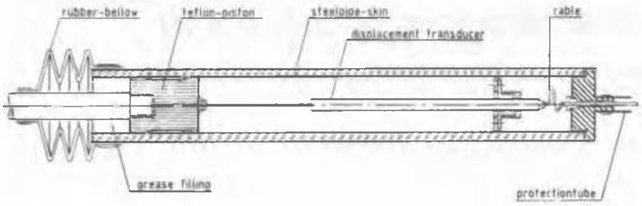

Fig. 3 Detail of the displacement-transducer

RESULTS OF MEASUREMENTS

Measurements were taken from the end of construction, figure 4. Between construction and beginning of reservoir filling there is no pronounced tendency of movements with the exception of measuring point 3, which shows a more or less marked displacement in the tail-water direction.

From the start of reservoir filling all three measuring points suffer from distinct oscillating displacements, showing a general tendency of movement towards tailwater. Seasonal variations indicate movements towards headwater during the cold period for all three points. Point 1 does not show as large amplitudes as the points 2 and 3.

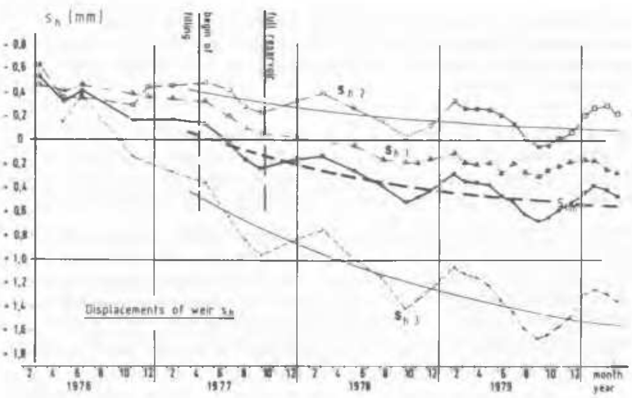

Fig. 4 Horizontal displacements of the measuring points 1 to 3 and median horizontal displacements

For example, fig. 5 shows typical changes in temperature at some points of the lock during one season. In general this kind of seasonal temperature changes must be assumed to occur at the weir, too. Direct measurements of temperature have not been possible.

EXPLANATION OF MEASUREMENTS

The acting of the building is explained using a theory for soil-friction interaction, based on a differential equation, developped by Matlock in 1951 (Seed and Reese, 1955).

The complete derivation of equations for the interaction between soil and concrete slab is given by Schulz, Feddersen, Weichert, 1980. They assumed perfect elastic-ideal plastic behavior for the soil-slab interaction (fig. 6).

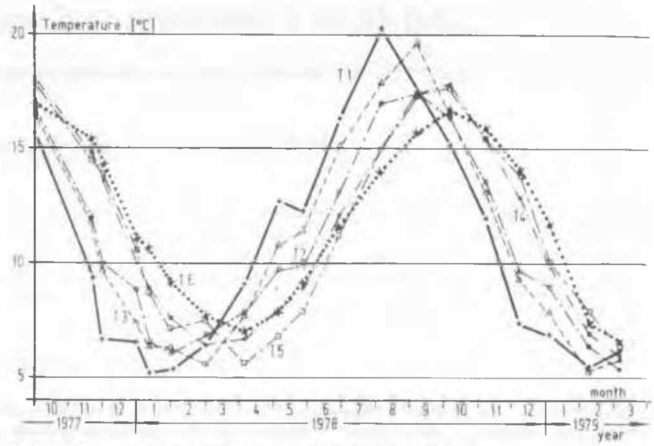

Fig. 5 Temperature-progress-lines

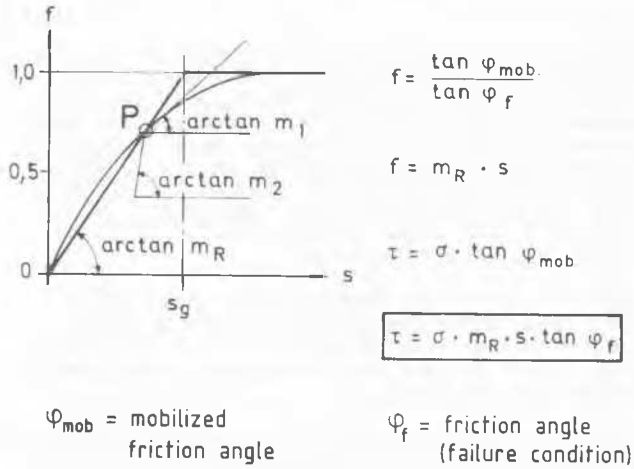

Fig. 6 Mobilizing of friction

This theory is from the type of transfere functions and is not capable to predict the movements of the half space beneath the considered building at the beginning of the displacements. Nevertheless this theory has the advantage against the theory of the elastic half space to take into account the very important influence of the distribution of contact pressures between foundation slab and ground.

With the details, given on figures 6 and 7 and with

$$\varepsilon = \frac{F}{A E_B} + \alpha \cdot \Delta t \qquad (1)$$

from the differential equation

$$\frac{d^2 s(x)}{dx^2} - r^2 \cdot s(x) = 0 \qquad (2)$$

where the friction parameter r is defined by

$$r^2 = \frac{3 \cdot \sigma \cdot m_R \tan \varphi_f}{A \cdot E_B} \qquad (3)$$

and m_R representing the stiffness properties of the interaction behavior one will get to the following expressions, which are valid for the linear elastic region of the working line:

$$s(x) = \frac{\varepsilon}{r} \cdot \frac{\cosh rx - \varphi \cdot \cosh r(L-x)}{\sinh rL} \qquad (4)$$

$$F(x) = A \cdot E_B \left(\varepsilon \frac{\sinh rx + \varphi \sinh r(L-x)}{\sinh rL} - \alpha \, \Delta t \right) \qquad (5)$$

$$T(x) = r \cdot A \cdot E_B \cdot \varepsilon \frac{\cosh rx - \varphi \cdot \cosh r(L-x)}{\sinh rL} \qquad (6)$$

In the above cited paper from Schulz et al (1980) further equations describing the plastic behavior of interaction are given.

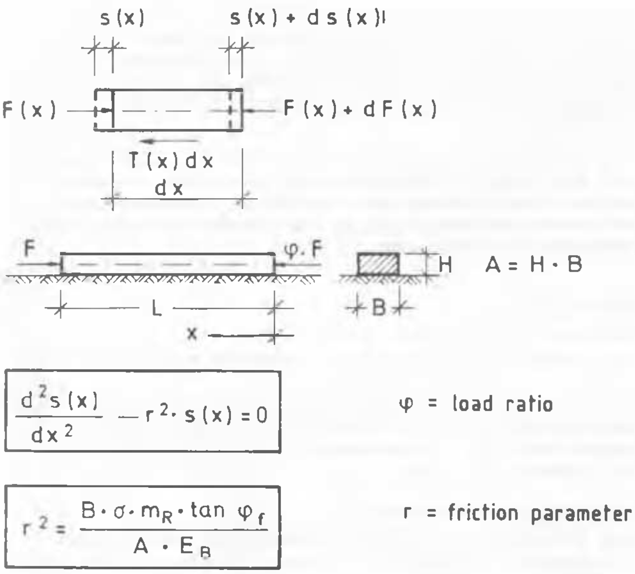

Fig. 7 Element of slab and whole slab with acting forces

If the point of zero displacement is defined by x = 0, then the load ratio φ is given by:

$$\varphi = \frac{1}{\cosh rL} \qquad (7)$$

Now let us assume a concrete slab that is loaded horizontal, then there is a certain distribution of shear stress in the plane of foundation. In case of an additional change of temperature Δt, due to change in the length of the slab, an additional shearing force will develop:

$$T(x) = r \cdot A \cdot E_B \cdot \alpha \cdot \Delta t \, \frac{\cosh rx - \varphi \cdot \cosh r(L-x)}{\sinh rL} \qquad (8)$$

Because of equilibrium of shearing stresses beneath the slab during action of Δt, one has:

$$\left| \int_0^{L_1} T_1(x)\,dx \right| = \left| \int_0^{L_2} T_2(x)\,dx \right| \qquad (9)$$

Equation (9) holds for the assumption, that the slab is divided into two parts at the point of zero displacement (x = 0), describing the parts L_1 and L_2.

For constant values of A, E_B and α along the slab from equ. (9) it follows:

$$\frac{r_1}{r_2} = \frac{L_2}{L_1} \qquad (10)$$

Thus equ. (10) gives the point of zero displacement depending on the friction parameter.

Now let us assume a horizontal slab on the ground. If it is not loaded, no shear stress will act. If there is a change in temperature this will result in identical displacements of all points, having the same distances to x = 0. If the slab is loaded horizontally by some load F, fig. 8, a non-linear distribution of shear stress will develop. For further explanation of the observed behavior we have to neglect the assumption of constant stiffness properties for the interaction behavior.

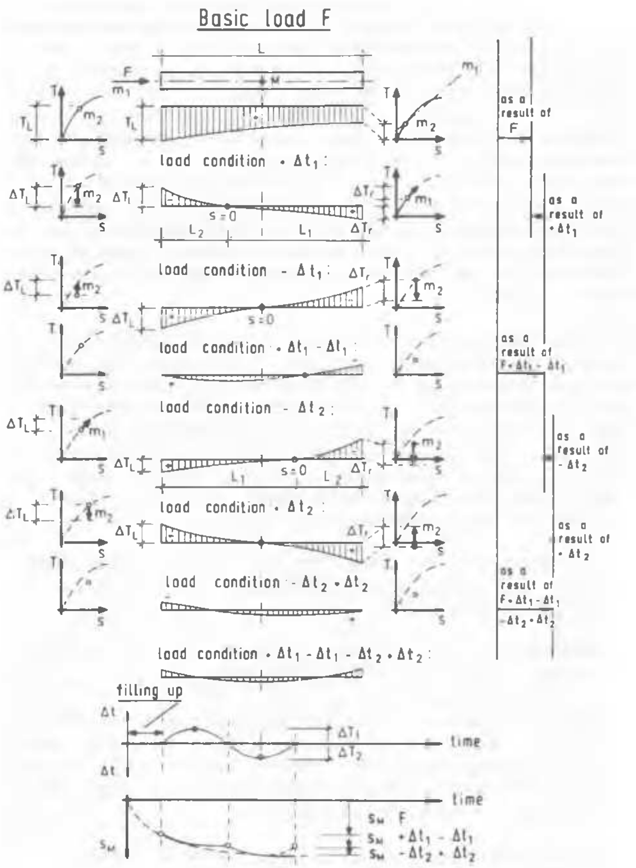

Fig. 8 Frictional force in the case of symmetrical change of temperature

With increasing temperature Δt the friction parameter r at both sides of the point of zero displacement will not be equal because of different values of m_R. This is schematically shown in fig. 6 at the location of point P. At this point unloading will result in the development of a much steeper working line, for instance with the angle arctan m_2, whilst loading in the same direction will give arctan m_1, and m_1 is a much smaller value than m_2 or m_R. At that side, where the displacement due to a change in temperature Δ t is directed against the acting load, that is at the left side of fig. 8, the friction parameter r will be on the unloading part of the working line in a shear force - displacement diagram and therefore r will be bigger than at the right side, where the working line will follow the loading part of the curve of soil-friction mobilization. So at this side the friction parameter r will be low and because of the validity of equ. (10) the point of zero displacement will be outside of the middle of the slab, or, with other words, the middle point of the slab will move in the direction of the acting load F.

Now we assume a temperature decrease of the same amount Δ t as the above described temperature increase. The friction parameter at the left side will be on the reloading part, at the other side of the point of zero displacement it will be at the unloading part of the curve of soil-friction mobilization. For convenience, the friction parameters are nearly equal, so the point of zero displacement will shift towards the middle of the slab.

Similar reflections for further temperature decrease Δ t, as given in fig. 8, will lead to the conclusion, that a horizontal loaded slab will show oscillating movements due to seasonal temperature changes and displacements in the direction of the external load, that will decrease after several transitions of temperature cycles.

If one wants to understand the observed behavior of the weir entirely, one has to look at the geometric circumstances of the building, the location of the measuring points and one has to obey the mathematical formulation of the friction parameter r given in expression (3) and the displacement s(x) given in equ. (4). Comparing the above mentioned factors, the following is to deduce:

- increasing r at some points within the same slab will lead to decreasing displacement at those points
- increasing r is given for increasing normal stress σ and increasing stiffness m_R
- measuring point 1 near the pillar with its rather high normal stress compared with that of the slab and near the - not exactly known - point of zero displacement will in fact show very small oscillations
- measuring point 3 with the rather large distance to the pillar will have the smallest normal stress of all three points and therefore the greatest oscillations with temperature changes as deduced from equation (4).

From detailed studying of fig. 4 it can be concluded, that the point of zero displacement has moved from the upstream side to the downstream side of measuring point 1 during the third season after filling the reservoir.

From fig. 8 one can deduce that due to seasonal temperature changes a gradually redistribution of shear stress will occur, concentrating the shear stresses in the middle part of the slab.

CONCLUSIONS

From the performed measurements in connection with a simple mathematical analysis, employing linear soil friction mobilization, but obeying different degrees of stiffness and therefore different amounts of mobilised stiffness parameters it was possible to show that horizontal loaded buildings perform oscillating movements due to seasonal temperature changes. In case of embedded structures this may lead to an increase of earth pressure. For buildings with a sufficient factor of safety against sliding the overall displacements will decrease and come to rest in spite of seasonal oscillating strains within the foundation.

The observed action of the weir of Iffezheim and the derived conclusions are also valid for all buildings with inclined foundation surfaces and especially for slabs resting on embankments (von Soos, 1979).

REFERENCES

Martens, W., Klose, H., (1975)
Die Staustufe Iffezheim, Wasserwirtschaft 65,9

Schulz, H., Feddersen, J., Weichert,H.-J.,(1980)
Zwängungskräfte infolge Sohlreibung, Mitteilungsblatt der Bundesanstalt für Wasserbau, Karlsruhe, Nr. 48

von Soos, P., (1979)
Die Stützung von Betonplatten auf geneigtem Untergrund, Festschrift zum 65. Geburtstag von o.Prof. Dr.-Ing. R. Jelinek, Lehrstuhl und Prüfamt für Grundbau und Bodenmechanik, TU München

List of symbols

A	cross-sectional area of slab
B	breadth of slab
E_B	Youngs modules of slab material
F	horizontal force acting on slab
L	length of slab
T	shear force acting between ground surface and slab
m_R	stiffness of soil-friction interaction
r	friction parameter
s(x)	displacement
Δ t	temperature change
x	coordinate
α	temperature coefficient
ε	dimensionless load
φ	load ratio
φ_f	angle of internal friction at failure
φ_{mob}	mobilised angle of internal friction
σ	normal stress