CHAPTER 166

GEOHYDRAULIC INVESTIGATIONS OF RUBBLE MOUND BREAKWATERS

BÜRGER, W.; OUMERACI, H.; PARTENSCKY, H.W.

Universität Hannover
Sonderforschungsbereich 205
Appelstrasse 9A, D-3000 Hannover 1, F.R.G.

1. Introduction

Due to the increase of ship sizes in recent decades a number of harbours and terminals have been built in deeper waters. Accordingly, the structures which have to provide protection against wave action become higher, too. In most cases, these protective structures are of the rubble mound type. Under such conditions the flow induced by waves within the breakwater and the related geotechnical behaviour of the rubble mound fill become more significant for the overall stability and should be considered in the design.

In addition, it is known that the scales usually adopted in hydraulic models (1:30 to 1:60) for investigating the stability of large rubble mound breakwaters generally lead to scale effects with respect to the flow field inside the breakwater. This means that small-scale model tests are not appropriate for investigating the internal flow patterns or for evaluating the pore pressure field induced by the incident waves in the core material.

Because of the uncontrolled conditions in the prototype, and since the actual permeability of the prototype rubble mound fill cannot be predicted (segregation, settlement, variation in grading, etc.), the use of large-scale physical models seems to be the most promising method for basic investigations of this kind. Moreover, the results of such large-scale model tests may be used to validate the usual smaller scale models and to calibrate numerical models.

Therefore, it is one of the objectives of our research programme on rubble mound breakwaters, which started in 1987, to concentrate on the evaluation of the wave-induced flow and pore pressure distribution within the breakwater.

The hydraulic model investigations have been essentially conducted in the Large Wave Channel in Hannover, F.R.G., and will be terminated in December 1988. It is the main purpose of this paper to present the first results of these model tests. However, a brief literature review related to the flow within rubble mound breakwaters and its effect on the overall stability is first given in order to show the necessity of developing reliable tools for the prediction of the actual internal flow field induced by storm waves.

2. Literature review

BARENDS et al. (1983) have demonstrated the importance of the internal flow field on the geotechnical stability of rubble mound breakwaters and applied a numerical model describing this flow for a number of existing breakwaters (BARENDS, 1985). Important improvements to this model were suggested by HANNOURA and Mc.CORQUODALE (1985). However, the reliability of such models is still limited, mainly due to the difficulties in simulating the complex phenomena involved, and to the lack of proper calibration. In this respect ALLSOP & WOOD (1987) have concluded from their most interesting and comprehensive literature review that there have been significant advances in the numerical modelling of the internal flow conditions in recent years, whereas measurements are extremely sparse.

On the other hand, measurements on small-scale model are not reliable because of the scale effects resulting from the lower permeability of the model core material. LE MEHAUTE (1957/1958) was the first to demonstrate the fundamental importance of a proper similitude of the rubble core permeability when investigating wave transmission aspects. The influence of core permeability on the stability of the armour layer has been demonstrated by BRUUN (1985), TIMCO et al. (1984) and VAN DER MEER (1985).

Although a number of investigations (LE MEHAUTE, 1957; DELMONTE, 1970; WILSON, 1971; KOGAMI, 1978) have been carried out on scale effects in modelling wave-induced flow within and through rubble mound structures, there is still no reliable method for the quantification and correction of these effects. The approach using scaling factors in the FROUDE modelling of the core material, as suggested for instance by LE MEHAUTE (1957/58), JENSEN & KLINTING (1983), and OUMERACI (1984), is very limited due to the unsteadiness of the actual internal flow; i.e. it is only valid for a specific hydraulic gradient.

In addition, it is known that slip-circle stability calculations according to BISHOP's method should include the excess pore pressure build-up induced by storm waves within the rubble mound structure and underneath the breakwater toe (BARENDS, 1984; BARENDS & CALLE, 1985). The most important characteristics needed for these calculations are the shear resistance parameters of the materials composing the foundation soil and the breakwater, as well as the maximum pore pressure distribution along a potential slip surface. Prototype measurements of the pore pressures within rubble mound breakwaters (HAKIMI et al, 1984) and underneath the breakwater (VAN IMPE, 1988) have also been performed.

However, a simple reliable method for assessing maximum pore pressure distribution under extreme wave loading and which is suitable for design purposes is not yet available. Such a method should include only the most relevant input parameters, i.e. the water depth and the incident wave parameters in front of the breakwater, the geometry of the structure and the hydraulic properties of the material composing the breakwater and the subsoil.

Well-calibrated numerical and hydraulic scale models may become reliable tools for developing simple relationships between these input parameters and the resulting excess pore pressure. Since the actual permeability of the prototype core and filter material cannot be predicted, the use of large-scale models as described below is most suitable for such calibration.

3. Experimental set-up

In the present research programme much effort has been concentrated upon the development of suitable instrumentation for measuring pore and soil pressure as well as the wave motion (wave run-up) directly at the interfaces between the various layers.

After small-scale tests were performed in the wave flume of the Franzius-Institut (110 m x 2.2 m x 2.0 m) with maximum wave heights up to 0.40 m, the same model was built in the Large Wave Channel in Hannover (320 m x 7.0 m x 5.0 m) in a scale 3.7 times larger. The tests are carried out by using monochromatic waves and JONSWAP-Spectra with $\gamma = 3.3$ and a Groupiness-factor of GF = 0.77. The wave maker is equipped with a SEASIM-wave absorption control. Maximum wave heights up to 2.5 m can be generated.

The waves are recorded in deeper water as well as in front of the structure by a 3 wave gauge-system in order to determine the incident and reflected wave energy. The position of the various wave gauges used is shown in Fig. 1.

In order to determine the variation of the wave-induced stress underneath the breakwater toe, three soil pressure cells and three pore pressure cells are installed in the sand bed layer. In addition, twenty pore pressure gauges are placed inside the rubble mound structure in such a way that the pore pressure distribution and the required boundary values for the calibration of numerical models can be gained with sufficient accuracy (Fig. 2).

One of the pore pressure gauges is shown in Figs. 3 and 4.

In order to follow the incident waves propagating in the armour and under-layer and penetrating into the core material three specially designed wave run-up gauges are also installed along the slope of the tetrapod armour, of the under-layer and of the core material (Fig. 2 and Fig. 6). The grain size distribution of the core material is shown in Fig. 5.

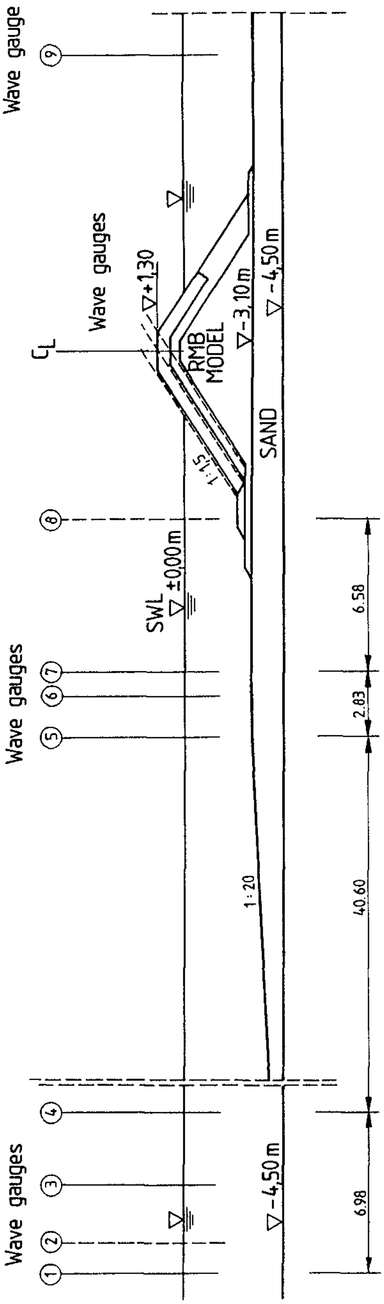

Fig. 1

Rubble mound breakwater model in the Large Wave Channel

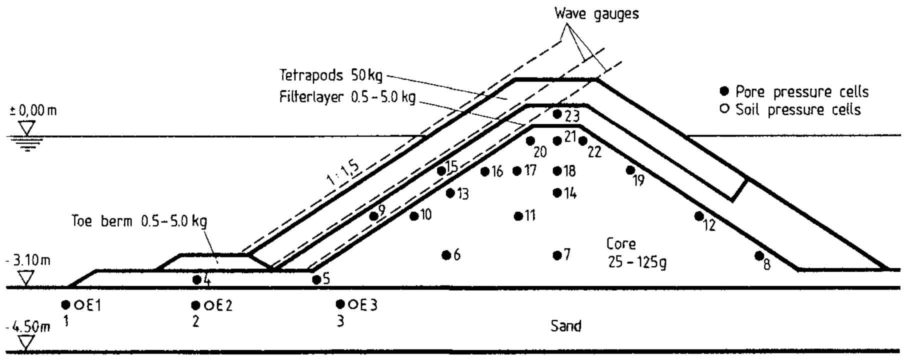

Fig. 2

Cross section of the instrumented large-scale model

4. First experimental results

Some of the first results of the performed model tests are presented in the following. A more detailed presentation and analysis of the final results will be published as soon as the test programme has been completed.

4.1 Wave reflection

Since wave reflection and energy dissipation are interrelated, and since little is known about the reflecting properties of tetrapod armours, the test results are fist analysed with respect to wave reflection. For the range of wave conditons tested ($2.5 \leq \xi < 6.0$), the following formula has been derived for the reflection coefficient K_R:

$$K_R = \frac{H_I}{H_R} = \frac{0.6\,\xi^2}{\xi^2+12} \tag{1}$$

in which:

H_I, H_R = incident and reflected wave height, respectively
ξ = surf similarity parameter
L = wave length
α = seaward slope angle of the breakwater

The surf similarity parameter is defined as follows:

$$\xi = \tan\alpha \,/\, \sqrt{H/L} \tag{2}$$

A reflection coefficient of K_R = 0.20 to 0.45 was obtained for the range of wave conditions tested.

These reflection coefficients are comparatively lower than those given by the relationship proposed by CERC (SEELIG, 1983) for natural stone armours.

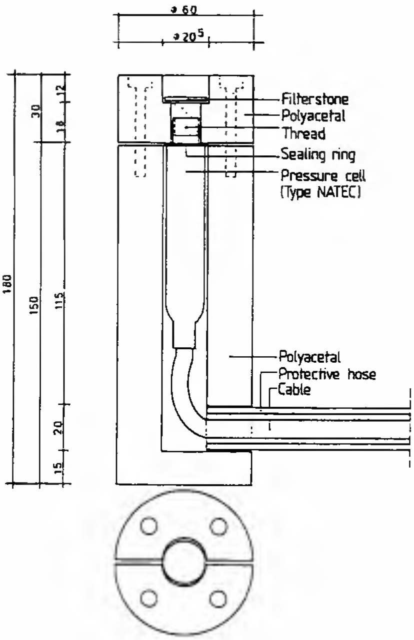

Fig. 3
Pore pressure gauge

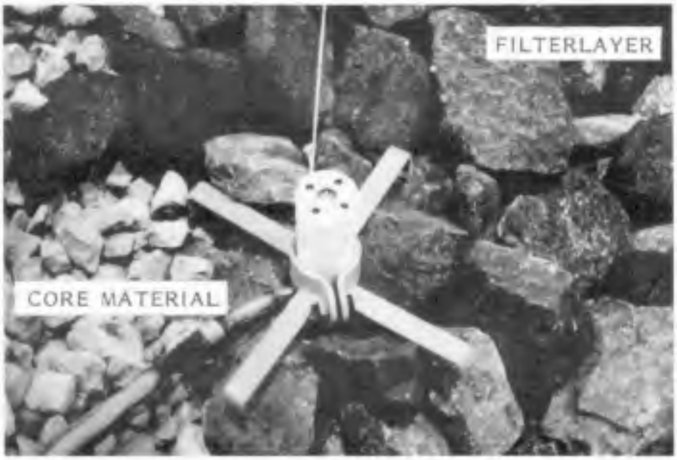

Fig. 4
Installed pore pressure gauge

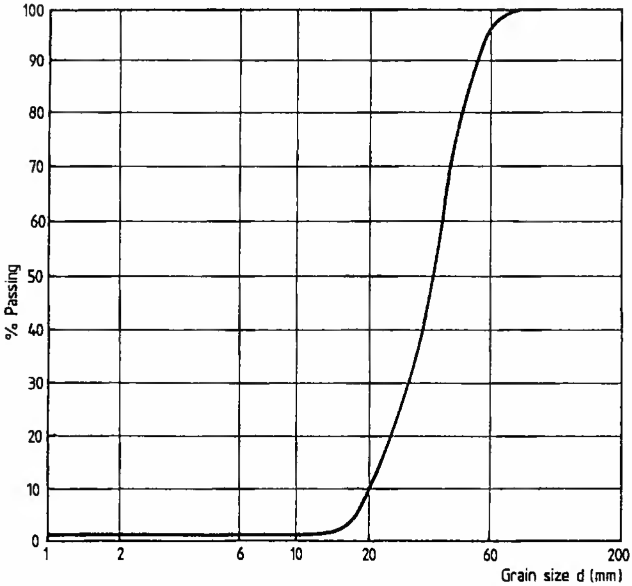

Fig. 5
Grain size distribution of the core material

Fig. 6
Pore pressure gauge and wave run-up gauge

4.2 Wave-induced pore pressure

One of the main objectives of the investigations by means of large-scale model tests is to measure and study the wave motion directly at the seaward face of the structure and the resulting wave-induced excess pore pressures inside the breakwater.

Typical examples of the waves simultaneously recorded by the 3 resistance-type wave gauges installed at the surface of the armour layer (WG 1), at the interfaces between the armour and filter layer (WG 2) and between the filter layer and the core material (WG 3), are given in Fig. 7 for incident waves with H_s = 0.73 m and T_p = 4.5 s in front of the breakwater. The corresponding pore pressure fluctuations induced in a horizontal plane and recorded at pressure cells PC 15-PC 19 (see Fig. 2 and 6) are shown in Fig. 8.

From these and further records it has been found that, in general:

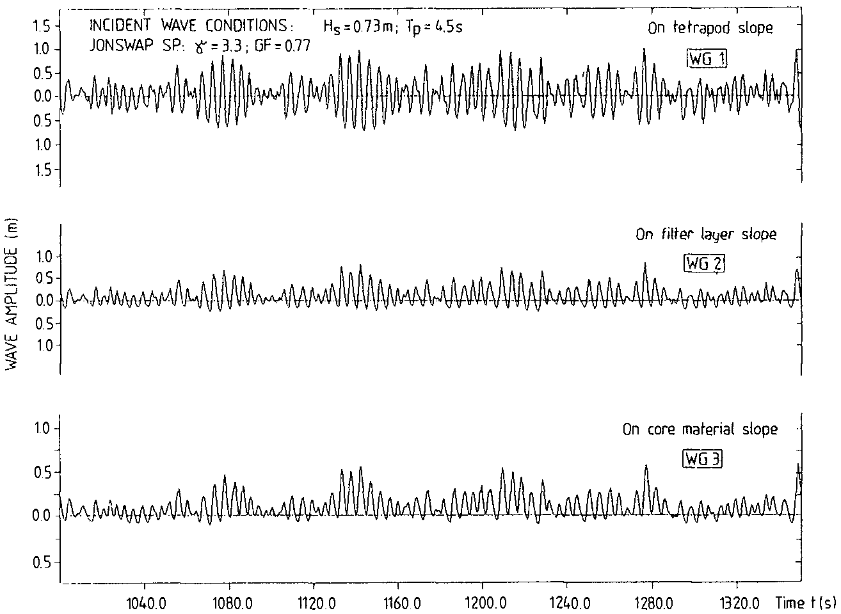

Fig. 7

Wave records at the interfaces
sea-tetrapode slope, filter layer-core material
(positions of WG 1, 2, and 3 see Fig. 2)

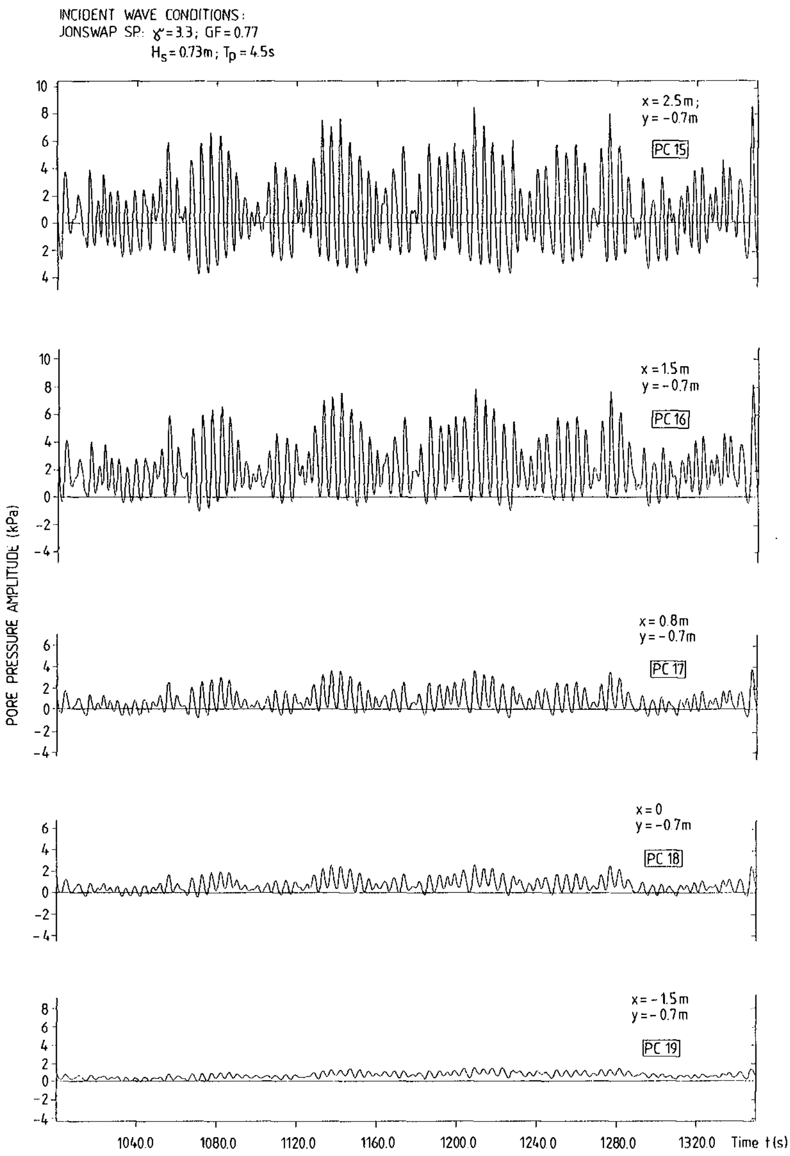

Fig. 8

Pore pressure fluctuations in a horizontal plane inside the breakwater (position of the pressure cells see Fig. 2)

- The frequency of the pore pressure fluctuations are of the same order of magnitude as the frequency of the incident storm waves;
- the incident waves induce a rise in the mean water level (setup) inside the rubble mound breakwater when compared with the sea water level outside the structure (10 - 20 % of the incident wave height);
- most of the incident wave energy is dissipated inside the armour and filter layer. The steeper the waves the more pronounced is this dissipation;
- the pore pressure amplitudes inside the breakwater decrease rapidely in the direction of wave propagation. This decay is more rapid for steeper waves.

The horizontal distribution of the maximum amplitudes of the excess pore pressure fluctuations induced by irregular waves at different elevations inside the breakwater and underneath the seaward toe is shown in Fig. 9. It can be seen that, particularly at elevations near the still water level, the maximum pore pressure amplitudes decay exponentially in the direction of wave propagation. Exponential decay of this kind has also been found theoretically by BIESEL (1950) for internal wave amplitudes. Fig. 9 and further similar results show that in deeper planes the amplitude decay becomes less pronounced.

Within the zone underneath the breakwater toe, however, the maximum pore pressure amplitudes tend to increase slightly in the direction of wave propagation. This is probably due to the more pronounced pressure build-up along the breakwater slope.

The distribution of the maximum pore pressure amplitudes at three different vertical profiles is shown in Fig. 10. From this and further results it is found that for the vertical profiles extending above still water level (SWL) the pore pressure amplitudes first increase and then slightly decrease with increasing depth. The maximum pressure amplitde is generally slightly below the still water level and depends upon the characteristics of the incident waves and the position of the vertical profile.

An interesting typical result is also shown in Fig. 11 for the distribution of the maximum pore pressure amplitudes along the slope of the core material and along another profile, parallel to the first, inside the core.

The results suggest, that:

- the pore pressure amplitudes do not decrease significantly in the direction normal to the slope;
- the position of the maximum value of the pressure amplitudes depends greatly on the depth of the profile considered.

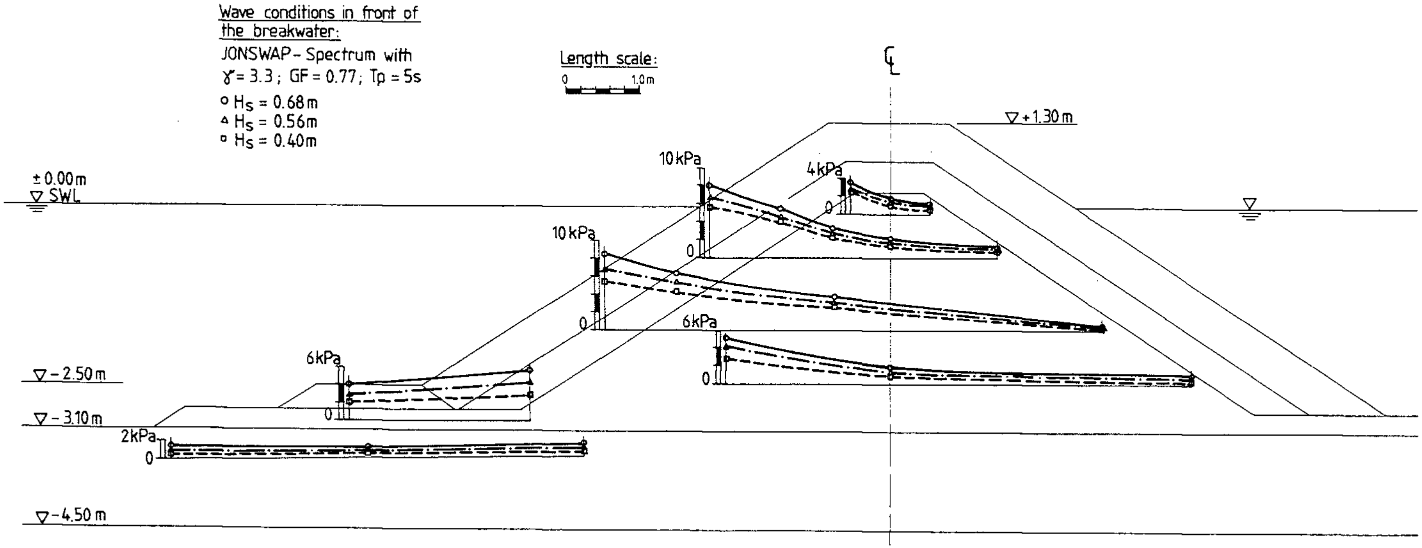

Fig. 9

Horizontal distribution of the maximum excess pore pressure amplitudes induced by irregular waves

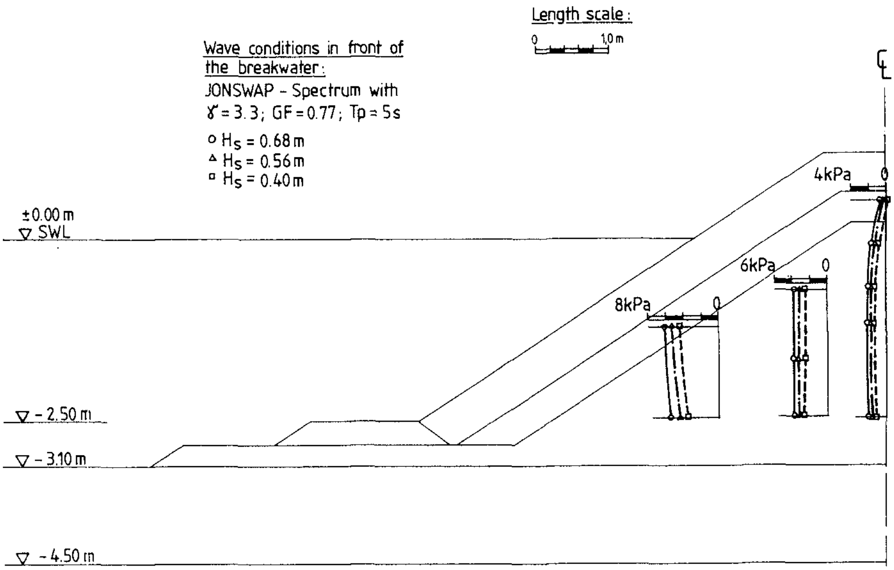

Fig. 10

Vertical distribution of the maximum excess pore pressure amplitudes induced by irregular waves

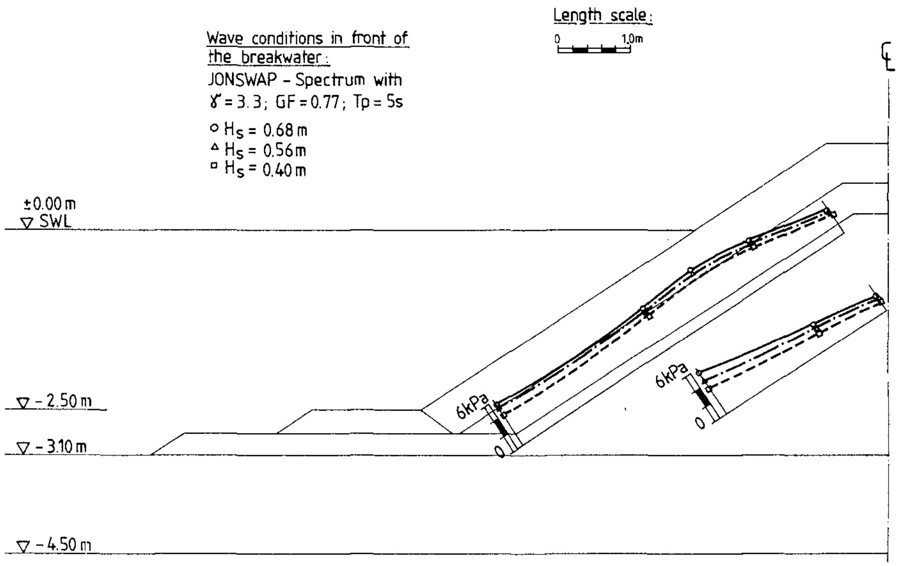

Fig. 11

Distribution of the maximum excess pore pressure amplitudes along the slope of the core material

5. Conclusion and perspectives

For the near future the problem of the wave-induced oscillatory flow inside rubble mound breakwaters will obviously not be amenable to an accurate analytical solution. This is due to a number of complex phenomena involved (breaking, air infiltration, unsteadiness and non-linear resistance of the flow, virtual mass effects, etc.) and uncertainties in the hydraulic properties of the porous media composing the breakwater.

Since a reliable method for quantifying and correcting scale effects in modelling wave-induced internal flow is still lacking and since an improvement and proper calibration of the existing numerical models by using results of large-scale model tests are needed, the analysis of the test results, which is underway, will focus particularly on these two aspects. Nevertheless, the first results and the literature review presented in this paper suggest that:

- Equation (1) for the reflection coefficient related to tetrapod armour layers would still be improved by including the results of small and large-scale model tests in the analysis;
- an empirical relationship between excess pore pressure and wave steepness (or surf similarity parameter) may be derived;
- an empirical or a semi-empirical equation for the decay of the pore pressure fluctuations within the breakwater in the direction of wave propagation should be formulated. For design application (slip-circle calculations), however, there is a need for simple formulae for approximately assessing the wave-induced pore pressures as a function of the water depth and the incident wave parameters in front of the breakwater. Unlike the approach in the hydraulic stability of armour layers, these formulae should be related to maximum wave loading;
- understanding of the interior process may be improved by including the transfer functions between wave and pore pressure fluctuations in the analysis. For the waves, use should be made of the recorded spectra at the interfaces sea-tetrapod slope and filter layer-core material.

6. Acknowledgements

This investigation is a part of a basic research programme in coastal engineering (SONDERFORSCHUNGSBEREICH 205) financed by the German Research Council (DFG). The authors are grateful to Dr. TAUTENHAIN and his staff at the Large Wave Channel, Hannover, for their help in the preparation and performance of the large-scale model investigations.

7. References

Allsop, N.W.H.; Wood, L.A.: "Hydro-geotechnical performance of rubble mound breakwaters - A literature review". Hydraulics Research Ltd. Rep. SR 98, Wallingford March 1987

Barends, F.B.T.; Kogel, H.; van der Uijttewall, F.J.; Haganaar, J.: "West-breakwater sines, dynamic-geotechnical stability of breakwaters". Proc. ASCE Conference Coastal Structures' 83, 1983

Barends, F.B.T.: "Probability of wave induced seabed instability". International Symposium on Maritime Structures in the Mediterranean Sea, Athens, 1984

Barends, F.B.T. & Calle, E.O.F.: "A method to evaluate the geotechnical stability of off-shore structures founded on a loosely packed seabed sand in a wave loading environment". Proc. of the 4th Intern. Conf. on Behaviour of Offshore Structures (BOSS' 85), Delft, 1985

Barends, F.B.T.: "Geotechnical aspects of rubble mound breakwaters". Proc. Conf. Breakwaters' 85, ICE, London 1986

Biesel, F.: "Equations de l'écoulement non lent en milieu perméable". La Houille Blanche, Mars-Avril 1950

Bruun, P. (editor): "Desgin and construction of mounds for breakwaters and coastal protection". Elsevier, Amsterdam 1985

Delmonte, R.C.: "Scale effects of wave transmission through permeable structures". ASCE Proc. of the 13th Conf. on Coastal Eng., Vancouver 1972

Hakimi, A.; Diouri, A.; Kaissoum, A.: "Contribution empirique à l'étude de la propagation de la houle à l'intérieur des digues". La Houille Blanche No 5, 1984

Hannoura, A.A.; Mc Corquodale, J.A.: "Rubble mounds: numerical modelling of wave motion". Proc. ASCE, Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 111, No. 5, Sept. 1985

Jensen, O.J.; Klinting, P.: "Evaluation of scale effects in hydraulic models by analysis of laminar and turbulent flows". Coastal Engineering, Elsevier, Vol. 7, 1983

Kogami, Y.: "Researches on stability of rubble mound breakwaters". Coastal Engineering in Japan, Vol. 21, 1978

Le Mehauté, B.: "Permeabilité des digues en enrochements aux ondes de gravité périodiques". La Houille Blanche, No.6, 1957; No. 2 & 3, 1958

Oumeraci, H.: "Scale effects in coastal hydraulic models". IAHR Symposium on Scale Effects in Modelling Hydraulic Structures, Esslingen, Sept. 1984

Seelig, W.N.: "Wave reflection from coastal structures". ASCE Proc. Conf. Coastal Structures, 1983

Timco, G.W.; Mansard, E.P.D.; Ploeg, J.: "Stability of breakwaters with variation in core permeability". ASCE Proc. 19th Conf. on Coastal Eng., Houston, 1984

Van der Meer, J.W.: "Stability of rubble mound revetments and breakwaters under random wave attack". Proc. Conf. Breakwaters' 85, ICE, London, 1985

Van Impe, W.F.: " Geotechnische Probleme beim Bau des neuen Hafens Zeebrügge". Geotechnik, 1, 1988

Wilson, K.W.; Cross, R.H.: "Scale effects in rubble mound breakwaters". ASCE Proc. of the 13th Conf. con Coastal Eng., Vancouver, 1972