Wave effects on blockwork structures: model tests

Effets des vagues sur des assemblages des blocs: tests sur un prototype

G. MÜLLER, *Lecturer, Civil Engineering Department, Queen's University Belfast, David Keir Bldg., Stranmillis Road, Belfast BT7 5AD, UK Tel.: +44 2890 274517, Fax: +44 2890 663754, e-mail: g.muller@qub.ac.uk*

P. HULL, *Consultant Engineer, Prof. Doran's & Partners, Belfast, UK*

W. ALLSOP, *Professor (Ass.) University of Sheffield / Manager Coastal Structures, HR Wallingford, UK*

T. BRUCE, *Lecturer, University of Edinburgh, UK*

M. COOKER, *Lecturer, University of East Anglia, UK*

L. FRANCO, *Professor, University of Rome 3, Italy*

ABSTRACT

Up to the middle of this century many coastal structures were built from blockwork, using either natural stone blocks or concrete blocks. Those blockwork structures subjected to breaking wave impacts often show a particular damage type, whereby individual blocks are shifted out of their position and moved into the sea. Engineers have suspected for a long time that wave impact pressures can travel into the water filled cracks and joints of such structures, building up pressures inside of the structure and thus destroying the structure from within. In order to verify the damage mechanism, and to investigate the characteristics of impact induced pressure pulses, model tests on the propagation of wave impact pressures into water filled cracks were conducted. It was found that impact generated pressure pulses can enter water filled cracks and that they exhibit wave-like characteristics such as finite propagation speed, reflection, superposition and attenuation. Changes in cross section were found not to affect pressure pulse magnitude or duration. The possibility of wave impact pressures to damage or destroy cracked or fissured structures from within the structure could thus be verified.

RÉSUMÉ

Jusqu'au milieu de ce siècle, de nombreux ouvrages côtiers ont été construits à partir de blocs en roche naturelle ou en béton. Ces assemblages de blocs soumis à l'impact des vagues déferlantes, présentent souvent un type de dommage particulier dans lequel certains blocs ont changé de position et se retrouvent dans la mer. Les ingénieurs ont supposé pendant longtemps que les pressions d'impact des vagues pouvaient se propager dans les interstices et les raccords remplis d'eau entre ces blocs, en générant des surpressions détruisant la structure de l'intérieur. Afin de vérifier ce mécanisme et de caractériser les impulsions de pression induites, on a testé sur modèle la propagation de l'impact des vagues dans les interstices remplis d'eau. Il apparaît que les impulsions de pression générées par les impacts, pénètrent les interstices remplis d'eau, et qu'elles présentent les caractéristiques d'une houle telles que : vitesse de propagation finie, réflexion, superposition et atténuation. L'intensité et la durée des impulsions ne sont pas affectées si l'on change les sections. L'hypothèse selon laquelle les pressions d'impact des vagues peuvent endommager ou détruire, de l'intérieur, des structures fendues ou fissurées, se trouverait donc vérifiée.

Introduction

Many older coastal structures such as sea walls, breakwaters or light houses, were built from natural or man made blocks, i.e. from rock or concrete. Even today, most coastal structures contain joints, required for construction or to allow for thermal expansion and/or differential settlement of the structure. Fig. 1 shows some typical examples of some old blockwork structures; a seawall built from dressed stones and the Aberdeen breakwater, which was built with concrete blocks. Many of these structures are subjected to the impact of breaking waves and the enormous pressures developed during these events. In the existing literature it is well recognised that cracks or joints in these structures often initiated damages to or led to the destruction of coastal structures. '*Wherever joints occur, either in rock or in artificial structures, both mechanical and chemical action proceeds the fastest. Apart from the inherent weakness of joints, the air or water confined within them, when struck by a wave, is converted into a very destructive agent*' [2]. These facts were repeated again, in a more modern language, in a more recent textbook. '*One practical indication of shock forces against concrete sea walls is the manner in which ill-designed or badly constructed lift joints become rapidly exploited by the sea*' [3]. Observations on damaged structures often show that wall elements are thrown out of the interlock towards the sea, indicating seawards acting pressures inside of the structure. Despite the importance of this subject, and its recognition by engineers for more than 100 years, little is known about the behaviour and characteristics of impact generated pressures in water filled cracks.

Literature review

General

The most severe forces experienced by coastal structures are caused by breaking waves. The slamming or impact loads consist of a very high but short pressure peak, possibly only lasting for one hundredth of a second but with magnitudes of up to 500

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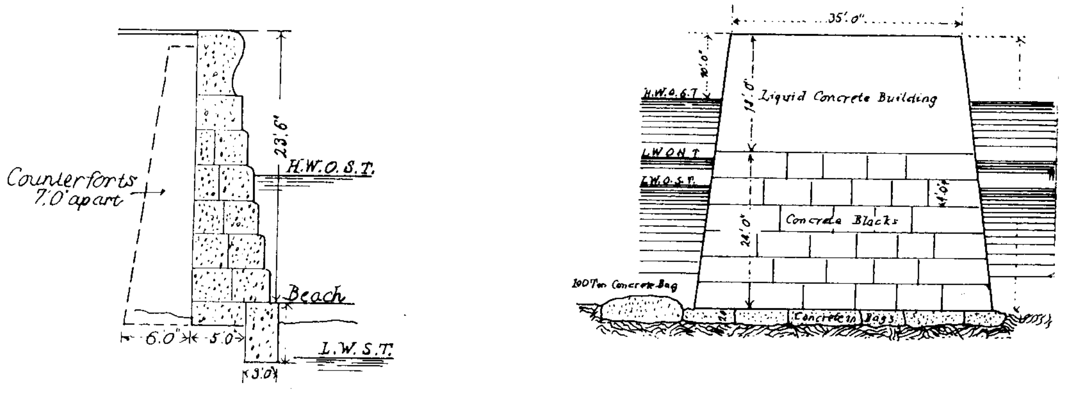


a. Concrete block sea wall at Margate, Bray & Tatham (1992)

b. South breakwater at Aberdeen 1873

Fig. 1 Cross sections of blockwork structures

kN/m^2 or more [4]. The pressure peaks are followed by a longer lasting but smaller hydrodynamic pressure, which is caused by the reflected wave crest. The impact pressures put severe loadings on structures, and may even travel into water filled cracks, pressing individual blocks outwards. Similar damage scenarios were reported from dykes with clay cover or revetment block protection, e.g. [5]. The suspected mechanism thus stresses the material where it is weakest, i.e. in tension, and initiates damage *from the inside* of the structure rather than from the outside. In [6] the possibility of blocks to be moved is illustrated with a sample calculation based on simplified assumptions.

Previous research

In previous experimental investigations it was found that wave impact related pressures could be observed at locations a distance away from the impact zone either on the sea bed, [7], [8], or underneath a caisson sitting on a permeable rubble mound [9]. In [7] and [8] it was shown that pressure signals larger than the hydrodynamic pressures caused by wave action could be observed on the sea bed in close proximity to the caisson or sea wall shortly after a wave impact had occurred. In [9] pressure measurements are described at four locations underneath a caisson model exposed to breaking waves. A wave like pressure signal was found to travel through the rubble mound underneath the caisson with a speed between 100 and 150 m/s. Although the authors termed this pulse a 'compression wave', no further mention was made of this observation and the effect itself was not investigated further. Measurements of impact pressures on a sea wall with a water-filled crack model of 0.5mm width, 25mm height and 100mm length are described in [10]. It was found that impact pressures can travel into water filled cracks, that they travel at a finite speed of approximately 100m/s and that the pressure pulses appeared to be reflected by the back wall. This was indicated by the pressure signal actually increasing towards the closed end of the crack. The exact interpretation of the measurement results was difficult, since the crack was very short compared with the length of the pressure pulse. Experiments with an open-ended crack showed that the propagation velocity dropped to 60 m/s, and that the pressure magnitude decreased towards the open end of the crack model. It was concluded that the pressure pulses in the crack appeared to show wave like characteristics quite unlike the hydrostatic pressure condition, which would have been expected for an incompressible medium [10]. Similar experiments with a 600mm long crack led to the incoming and reflected wave being spaced further apart [11]. Previous assumptions were confirmed, with wave reflection in particular being better identifiable. A new set of experiments was thus prepared to investigate the properties of the compression pulse in a longer crack model, and some initial results were presented [12], [13].

Experimental setup

Wave tank and models

The experiments were conducted in the Hydraulics Laboratory at the Queen's University of Belfast's Civil Engineering Department in a wave tank of 17m length, 350 mm width and a water depth of 1m. An inserted false bottom made of fibreglass brought the water depth from 1m at the deep end to 110mm at the model sea wall with a slope of 1:10 as shown in Fig. 2. Measurements were conducted for two crack models:

1. A model of a crack of 0.5mm depth, 10mm width and a total length of 2225mm, see Fig. 3, which could be inserted into the wall. The crack model was manufactured in four sections (crack 1 – 4), which could be joined to form cracks of varying

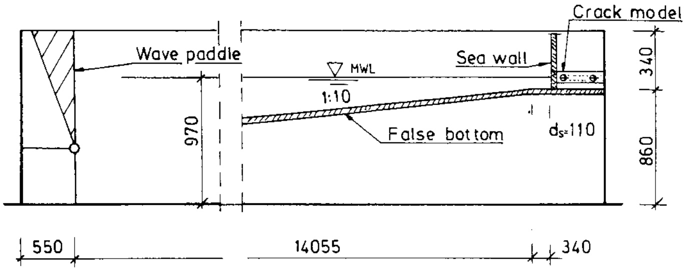


Fig. 2 Wave tank with false bottom and sea wall (all dimensions in mm)

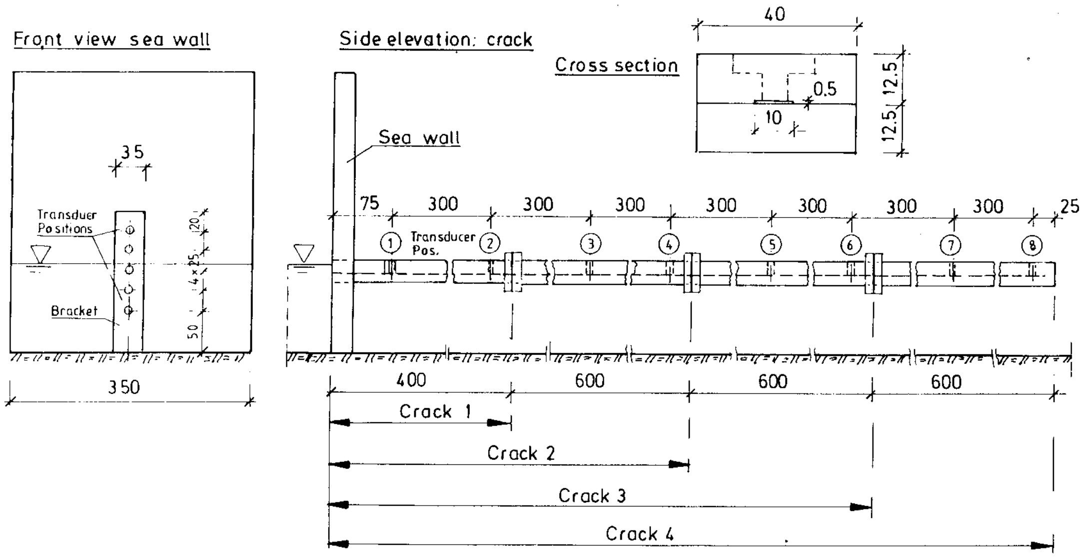


Fig. 3 Crack models 1 – 4 (all dimensions in mm)

length. The crack opening was located 10mm below the still water surface. The crack was built from Perspex with outer dimensions 25×40mm. Fittings for pressure transducer were provided at distances of 75, 375, 675, 975, 1275, 1575, 1875 and 2175mm distance from the crack entry.

2. A vertical crack of 0.5mm width, 25mm height and 600mm length with a 100mm long cavity of 25mm diameter at its end. The crack entrance was completely submerged. Transducer positions were provided at 100mm distances and at the end of the cavity.

The pressures were measured with 5 ENDEVCO 8510B-5 pressure transducers with a maximum capacity of 35.4 kN/m^2 and a natural frequency in air of 180 kHz. The data was acquired using purpose written high-speed data acquisition software with 4000 samples per second per transducer.

Experimental procedure

In order to generate a clean and repeatable plunging breaker, a wave train consisting of three sinusoidal waves of period T = 1 second, and a deepwater height of 71mm was generated by the wave paddle every 150 seconds. The first wave to arrive at the sea wall produced, since it was undisturbed by any previous breaker, a violent plunging breaker against the model wall. Only the pressures generated by this first breaker were recorded. Due to the size of the pressure transducers, pressures at the sea wall could not be measured simultaneously with pressures in the crack model. The model sea wall contained a fitting for either a bracket for transducers or for the crack model. The bracket with five transducers, as shown in Fig. 2 (left), which fitted into the slot for the crack, was inserted first and pressures were measured at the face of the wall exactly at the location where the opening of the crack would be. After five events had been recorded, the first bracket was replaced with the bracket which contained one of the crack configurations. All visible air bubbles were removed by siphoning water through the crack. Once each set of investigations was completed, the crack and second bracket were removed and the original bracket replaced so that pressures could be recorded again on the front face of the model vertical wall. Five events were again recorded and compared to pressure readings before the insertion of the crack, to ensure that the similar pressures occurred on the open face of the crack throughout the investigation. For all crack configurations, four test runs were conducted in order to examine the repeatability of results.

Experimental results

General

In all, four different sets of experiments were conducted:

1. Measurements of wave impacts on vertical wall.
2. Measurement of pressures in cracks of varying length (400, 1000 and 2200mm)
3. Pressure pulses in cracks with open and closed ends (l = 1000mm).
4. Pressure propagation into cavities.

Wave impact on a vertical wall

In Figure 4, ten pressure-time traces for wave impacts at the location of the crack entrance (but without the crack) are shown. Five were taken before, and another five after a crack measurement. It can be seen that the pressures are very repeatable, indicating that a carefully controlled breaking wave was produced. This repeatability is necessary for the experiments, since pressures cannot be read on the front face and inside the crack at the same time. The pressures ranged from 16.55 to 22.68 kN/m^2, with an average value of 20.74 kN/m^2 and a standard deviation of 11%. Compared with previously reported test results even with regular waves, the impact pressures appear to be very repeatable. This did however only hold for one test; even though extreme care was taken to recreate all experimental conditions it was found that in particular impact pressure magnitudes were variable between test series separated by longer periods of time. The effect of these differ-

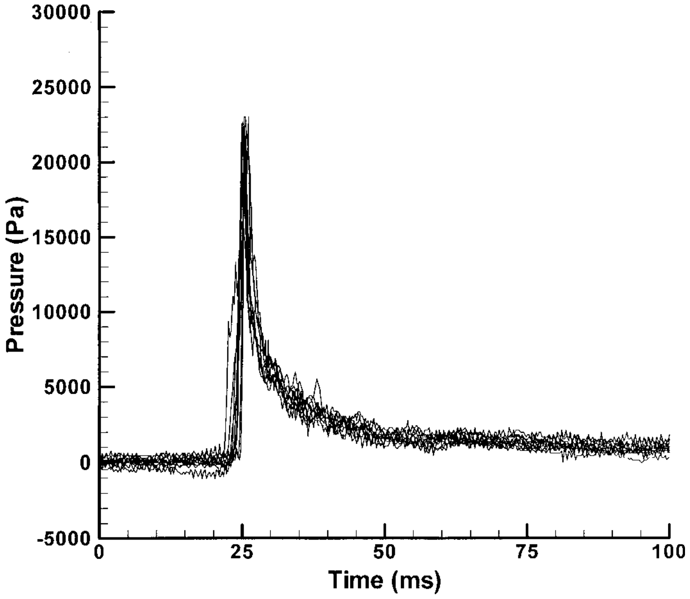


Fig. 4 Wave impact pressures on sea wall model

ences were not considered as very important since the pressure pulse in the crack was not so much affected by the actual peak magnitude but by the impact impulse, which is by far not as variable as the peak magnitude.

Pressure measurements in cracks 1 and 4

The results from the tests on crack 1 are shown in Fig. 5a, with the results of five tests superimposed to demonstrate the repeatability of the results. The pressures at position 2, near the end of the crack, are slightly larger, due to the reflection at the end of the crack, and more regular than those measured near the entrance. The pressure traces at Pos. 1 also indicate the reflected wave as a second maximum. In Fig. 5b (crack 4), the pressure magnitude decreases significantly from the crack entrance, P_1 = 4845 Pa, towards the end of the crack, with P_5 = 1928 at x = 1375mm, P_6 = 926 Pa at x = 1675mm (not indicated in the figure) and P_6 = 1457 Pa at the reflective end of the crack. Here only one measurement is shown to keep the picture clear. The pressure increase at the end of the crack indicates that the compression wave is reflected. The incoming and outgoing pressure pulses can be clearly identified at position 5.

The propagation velocity can be determined between positions 1 5 or 1 and 8 as around 60 - 90 m/s. A more accurate determination of the velocities is difficult for the following reasons:

1. The pressure pulse attenuates through energy losses; i.e. the pulse becomes longer and shallower.
2. Because of this, the point of maximum pressure can not be used for the determination of the velocity; the onset of the pulse should be used.

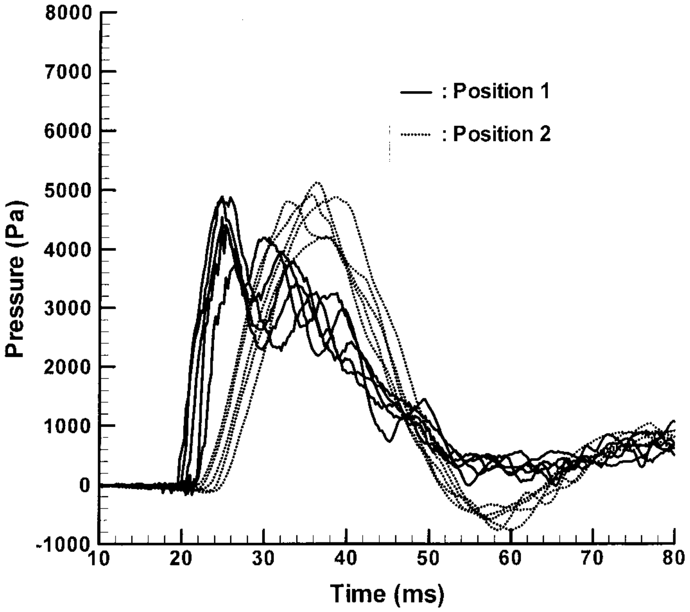
This onset is however difficult to differentiate from noise and possibly the effect of the returning reflected pulse.

Pressures in cracks with open ends

One set of experiments was conducted with the 1000mm long and 10×0.5mm wide crack model 2. The pressures were measured with the end of the crack closed and open. Fig. 6 shows the pressure pulse in the crack for the open and closed end conditions.

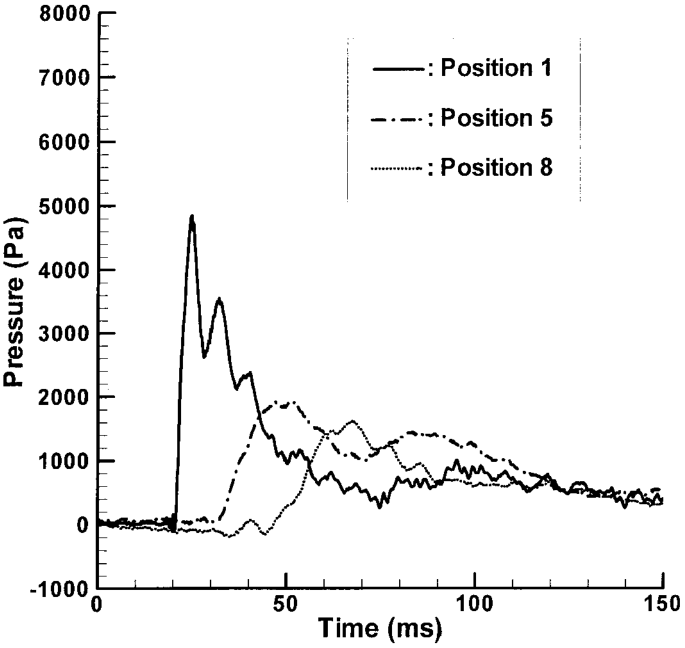
Open end (Fig. 6a): the pressure magnitude decreases fast, whilst the pressure pulse assumes the very regular shape resembling a solitary wave at Pos. 3. The pressure transducer at position 4, only records a small signal, which is thought to be caused by the compression wave travelling inside the perspex containment.

Closed end (Fig. 6b): the pressure pulse travels into the crack, and is reflected at the closed end. it The reflected pressure pulse



a. Pressures in crack 1 (l = 400mm)

Fig. 5 Pressure propagation in cracks 1 (l = 1000mm) and 4 (l = 2200mm) a. Pressures in crack 1



b. Pressure in crack 4 (l = 2200mm)

Fig. 5 Pressure propagation in cracks 1 (l = 1000mm) and 4 (l = 2200mm) b. Pressures in crack 4

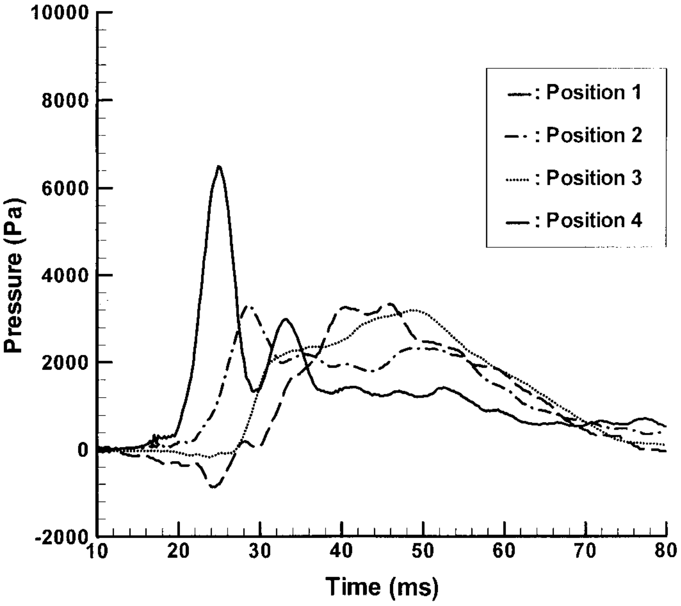


Fig. 6 Effect of open end on pressure propagation
a. Pressures in crack 2 with closed end

leads to a much larger magnitude and longer duration of the pressure inside the crack, caused by the superposition of incoming and reflected pulse. Fig. 7 finally shows the highest recorded pressures at each transducer location for open and closed crack. In combination with Fig. 6, it demonstrates two effects:

1. The open end enforces a zero pressure condition.
2. The end condition affects pressure magnitudes only in its vicinity.

From Fig. 6a, Pos. 3, the approximate length of the pulse can be determined as 2.2m. The effect of the closed end ranges with 0.5m to approximately 25% of the length of the pressure wave. Obviously these are very rough estimates since the pulse speed and length are difficult to define, and the pulse length increases with the propagated distance.

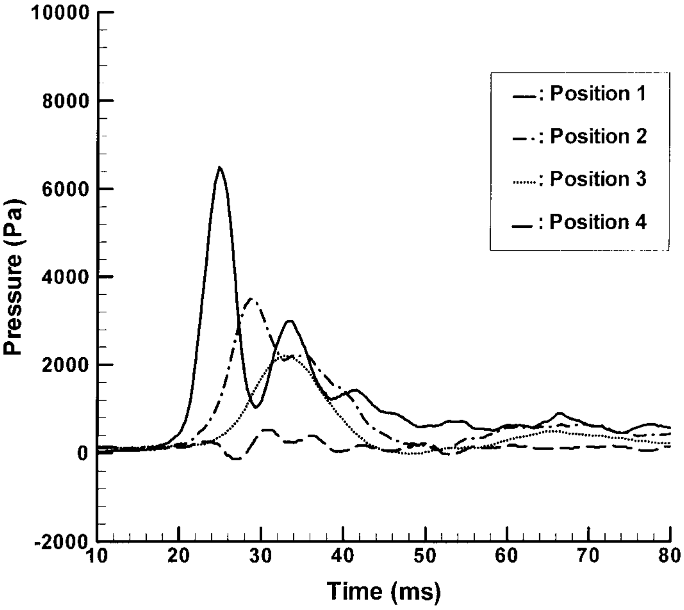


Fig. 6 Effect of open end on pressure propagation
b. Pressures in crack 2 with open end.

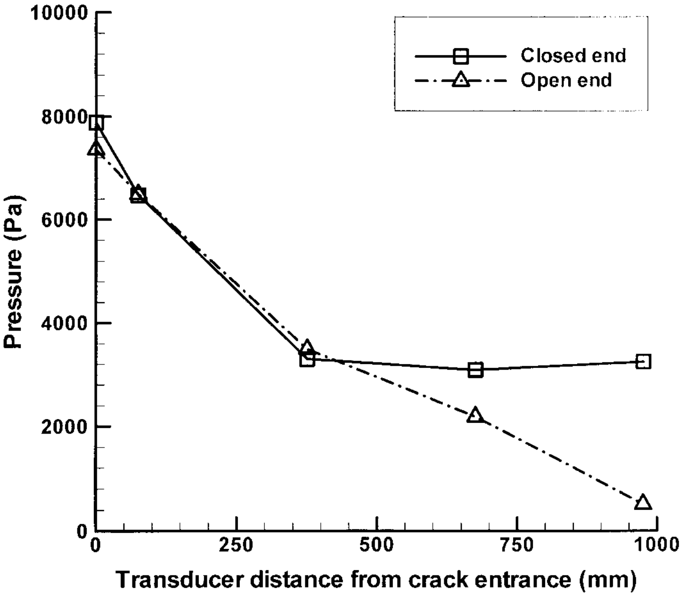


Fig. 7 Maximum pressures at locations 1-4 for open and closed end (crack 3)

Pressures in an end cavity connected to the crack

In reality, cracks will not have a constant cross section and may well end in or pass through small cavities. In order to investigate the effect of a sudden expansion, a 600mm long crack of 25mm height and 0.5mm width was inserted into the model sea wall. A 100mm long cavity with an internal width of 25mm made of Perspex with 10mm wall thickness was added at the end of the crack as is shown in Fig. 8. Two sets of measurements were conducted; one without the cavity and with closed end of the crack (series 1), and one with the cavity attached to the crack (series 2). The impact pressures, i.e. the pressures at the crack entrance, were of similar magnitude for both experiments with a maximum pressures of 16.2 kPa and a standard deviation of .175 for the experiments without, and a maximum pressures of 14.15 kPa and a standard deviation of 0.29 for the experiments with the cavity. Transducers were located at the crack entrance (Pos. 1), near the cavity entrance (Pos. 6) and at the end of the cavity (Pos. 7). The results of five measurements are shown in Fig. 9. Fig. 9a and b

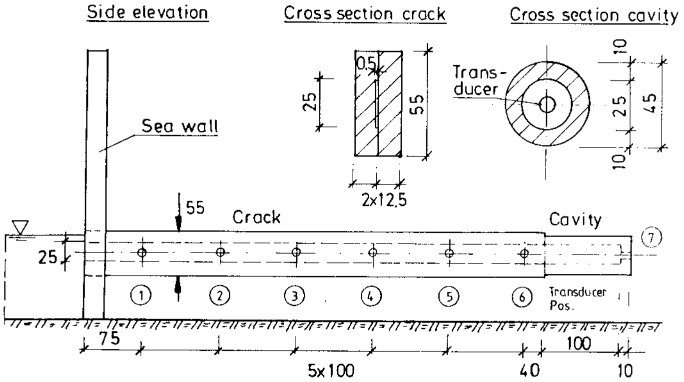


Fig. 8 600mm crack model and cavity (all dimensions in mm)

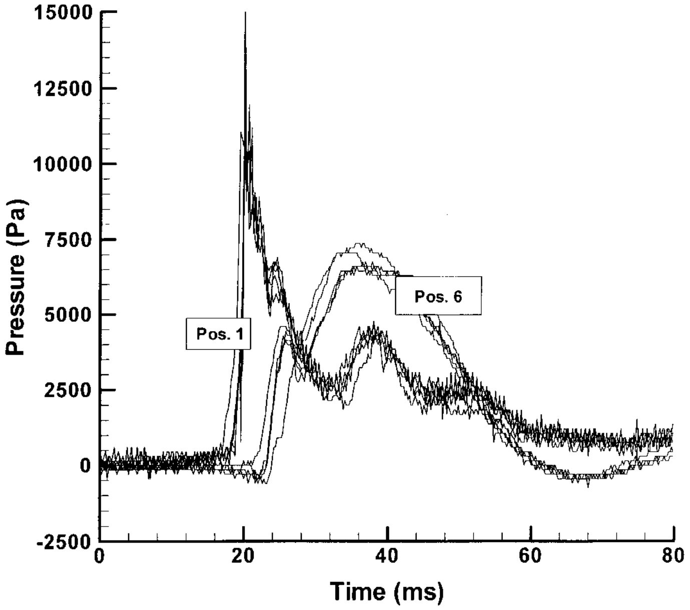


Fig. 9 Pressures in crack and cavity
a. Pressure at positions 1 and 6 in the crack without cavity

show pressures measured near the crack entrance, at Pos. 1, and the pressure pulse at Pos. 6, near the end of the crack for series 1 without cavity in Fig. 9a, and near the cavity entrance for series 2 in Fig. 9b. Although the pressure record at Pos. 6 will contain at least parts of the pressure pulse reflected by the closed end of the crack, it can be seen that the magnitudes of the pressures at position 6 and 7 are quite close, with maximum pressures of 7204 Pa for Fig. 9a, 6465 Pa for 9b. The comparison between Fig.'s 9a and b shows that the cavity has little influence on the pressure in the crack and Fig, 9c indicates that the pressure in the cavity is with 6465 Pa for 9c similar in magnitude to the pressure in the crack. The magnitude and duration of the pressure pulse travelling out of the crack and into the cavity thus are virtually unchanged, despite the fact that the cavity has a cross sectional area which is 39 times larger than the crack.

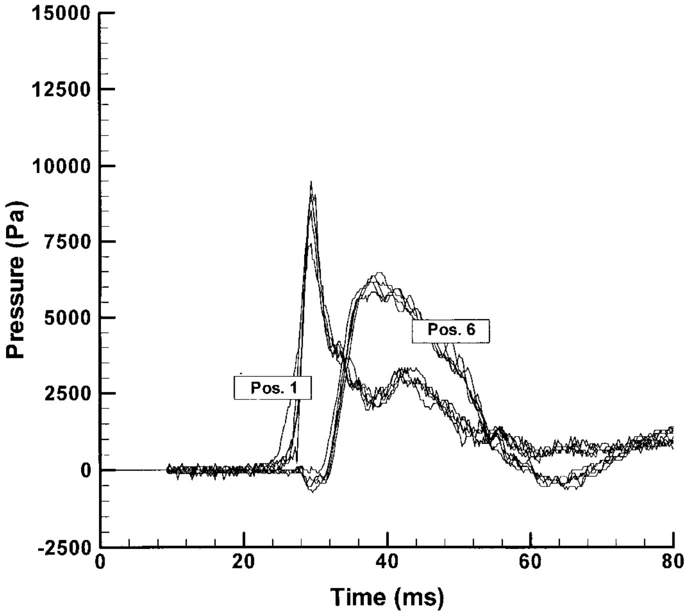


Fig. 9 Pressures in crack and cavity
b. Pressure at Pos. 1 and Pos. 6 near crack end

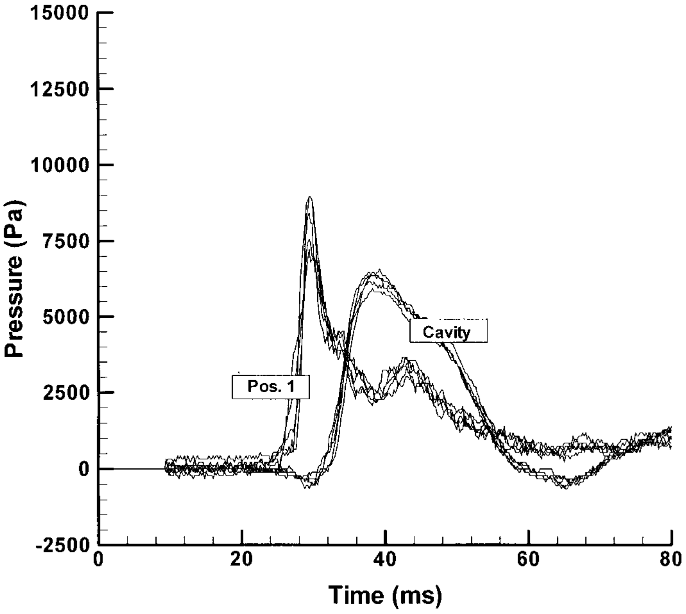


Fig. 9 Pressures in crack and cavity
c. Pressure at Pos. 1 and at the end of cavity

Effect of containment elasticity and aeration

The observed propagation velocity of the pressure pulse lies well below the speed of sound of water (1450 m/s) or air (330 m/s). The actual speed of propagation of a signal in a contained fluid can be affected by the elasticity of the containment or by the elasticity of an enclosed gas volume. The propagation velocity of a pressure wave in water filled pipelines is a function of the pipe wall elasticity and the aeration ratio α; with increasing pipe wall elasticity and aeration ratio the speed of propagation decreases. For a thin walled pipe of diameter d, wall thickness e and elastic modulus E the speed of propagation of sound c can be determined as follows [14]:

$$c = \sqrt{K_{eff} \ / \ \rho} \tag{1}$$

$$K_{eff} = \left[(1 - \alpha) \ / \ K_f + \alpha \ / \ K_g + d \ / \ Ee \right]^{-1} \tag{2}$$

K_{eff} : effective bulk modulus of fluid, gas and pipe
K_f : bulk modulus of fluid, 2.0×10^9 Pa
K_g : bulk modulus of gas, 1.0×10^5 Pa
α : aeration ratio
ρ : specific density of fluid

As a first approximation, it is assumed that the thin wall assumption (i.e. only hoop stresses, no bending), is also valid for thick walled pipes. Although this assumption does not hold for the equivalent diameters calculated in the following, the simplified calculation will nevertheless give an indication of the magnitude of the effect of wall elasticity. With $E = 2.5\times 10^9$ Pa for Perspex, an equivalent wall thickness *d* of 17.4mm and an equivalent pipe diameter *e* of 2.52mm (transforming the rectangular cross section into an area equivalent circular cross section), this formula gives a reduction of the speed of sound in water without aeration from 1450 m/s to 1338 m/s. The effect of wall thickness on the speed of sound is thus below 10%, and can not explain the observed pulse propagation velocities of 60 - 90 m/s. This low velocity can only be explained if the water contains 1.5 – 2.5% of entrained air, thus constituting a 2-phase medium.

Discussion

The model scale experiments showed that the propagation of wave impact pressures into water filled cracks is possible, confirming the assumptions made about this effect as the reason for damages to coastal structures. The rapid decrease of pressure magnitude as the wave progresses into the crack indicates that strong energy dissipation occurs. From the measurements alone, and from basic fluid mechanics, these losses can not be explained. Usually, energy dissipation in fluid flow is attributed to viscosity. In case of the pressure propagation through a closed crack, fluid flow is impossible, so that the losses have to be attributed to some other mechanism. It was shown that high energy dissipation in bubbly fluids can occur through isothermal compression of the air bubbles [15]. Typically, a bubble of 0.1mm diameter has a thermal time of 0.05ms, so that small bubbles dissipate all their thermal energy much faster than the pressure signal changes [16]. The heat generated during the compression of the air bubble is dispersed much faster than the rise time of the compression pulse due to the much higher heat capacity of the water compared with that of the air. The temperature in the air bubble thus remains the same as that of the water, and the energy absorbed during the compression is dissipated. This effect requires further more detailed investigation.

The experiments with a cavity showed that the pressures in the crack did not reduce when approaching or entering a much larger cavity. This rather puzzling result leads to the conclusion that cavities which are small in length compared with the length of the pressure pulse will probably be filled by the pressure pulse completely, without any drop in magnitude, so that large internal forces can develop inside a structure with internal cavities.

The demonstration of wave impact induced pressure pulses travelling through also leads to some interesting outlooks on the character of actual wave impact pressures. If a compression wave enters the crack, another symmetrical wave must travel away from the crack entrance, resulting in pressures travelling along the seabed. The attenuation of the pressures, in combination with the dispersion in the 'open' environment of the sea, would then also lead to strong pressure gradients along the seabed.

Limitations

Although the measurements revealed quite a few characteristics of the impact induced pressure pulse, the actual application of the results to real problems remains difficult for three reasons:

1. No scaling law exists for wave impact pressures. Although some progress was made recently it is as yet not possible to scale either magnitude or duration of impact pressures from model test to full scale [17].
2. Observed aeration levels in sea water are higher than in fresh water since sea water retains air bubbles more easily and since waves tend to be more turbulent at full than at model scale [4].
3. Pressure magnitudes at full scale exceed atmospheric pressures by a significant amount, so that the air spring will become non-linear. This further complicates the scaling.

A fourth problem lies in the fact that the length of the pressure pulses will not scale with the linear scale factor either. In order to obtain dynamic similarity between structure and model, the ratio of wavelength to crack length however has to be similar for the model and the full-scale structure.

Conclusions

A series of model tests showed that the propagation of wave impact pressures into water filled cracks may indeed be the reason for damages to blockwork coastal structures. The experiments described in this article showed impact generated pressure pulses to travel into long water filled cracks, whereby the pressure magnitude decreased with increasing travel distance. The observed propagation velocities of the pressure pulses indicated that the water inside the crack model must contain 1.5 – 2.5% of air in the form of microbubbles. The energy losses indicated by the attenuation of the pressure pulse could not be explained with viscous losses, since very little mass flow is taking place, and have to be attributed to another compression-related mechanism. The investigation of cracks with an open end showed that a ventilated end will only affect pressures in its vicinity. A sudden expansion of the crack did not reduce the pressure magnitudes, so that the development of large forces inside of structures (e.g. in the cavity behind an individual block) can be expected.

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