CHAPTER 173

WAVE-INDUCED SHOCK PRESSURES UNDER REAL SEA STATE CONDITIONS

by

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ABSTRACT

This paper deals with a study on shock pressures, which occur on sloping seadykes and revetments due to breaking waves. Results from field measurements are presented with respect to peak pressure values as well as to characteristics of pressure-time histories.

1. INTRODUCTION

Investigations on shock pressures, especially at vertical walls, have been done since 140 years. Tests mostly have been carried out in small scale models, only a few measurements have been done in field or in laboratory full-scale (for vertical walls see e.g. Blackmore, Hewson (1984), for sloping seadykes see e.g. Stive (1984), Führböter (1986), Führböter, Sparboom (1988).

Furthermore in laboratory tests mostly regular waves were used or irregular waves were not really related to the topographic relations in front of excisting seadykes in nature.

The published data from the different investigations often show considerable differences especially with respect to maximum peak pressure values. It can be no doubt, that these differences mainly are a result of the different wave characterstic conditions. The wave characteristic conditions itself strongly influence the amount of air entrainment, therefore considerable scale effects can occur in small-scale models. Due to the more or less unsolved problems with these scale effects and due to the random characteristics of waves under real sea state conditions there still is a great need for detailed field data, to verify investigations in laboratory, even such in full scale.

2. FIELD MEASURING EQUIPMENT

The data presented in this paper, have been measured in field at two different locations at the coast of the German Bight during several storm surges (Grüne, 1982).

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At the EIDERDAMM location two different sections were used: the original adjacent dam of the Eider-storm-surge-barrier, which has a bended slope of 1:4 in the lower and 1:6 in the upper part, and additionally a testsection with a uniform slope of 1:4 (Fig. 1). On both sections upwards from $NN + 3.00m$ (which is roughly $1.5m$ above Mean High Tide) the cover layers are made from asphalt-concrete on a sand core. On these asphalt-covers the wave-induced pressures were measured synchronously on both slopes with up to 5 pressure cells, which had a vertical distance of roughly $25cm$ from each other (on both slopes).

The section used at the east-frisian island WANGEROOGE, has also a cover layer made from asphalt-concrete on a sand core with a nearly constant slope of 1:4. Up to 25 sensors with a vertical distance from each other of only $9cm$ have been used synchronously to measure the wave induced pressures on the surface.

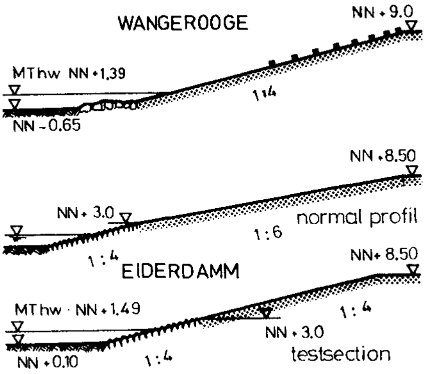


Fig. 1 Dyke profiles used for field measurements at both locations

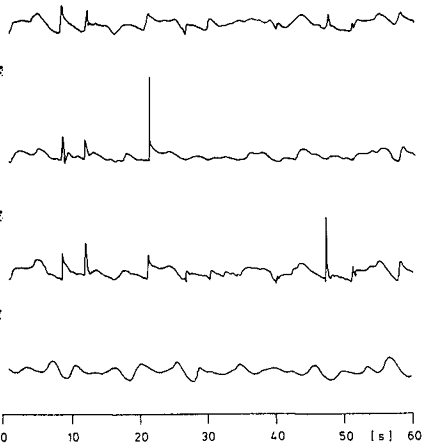


Fig. 2 Example of a synchronous record from some pressure cells on slope 1 : 4 (EIDERDAMM location)

Waves at both locations were recorded also with pressure transducers. These pressure data have been transfered to surface elevations by means of correction factors for the statistical wave parameters in time domain, found in model tests and verified by field measurements (Grüne, 1982).

3. ANALYSIS OF WAVE-INDUCED SHOCK PRESSURES

The definition of shock pressures from field records of wave-induced pressures, especially measured on slopes, is more complicated than for laboratory data with idealized boundary conditions. Due to air entrainment of breakers and the occurrence of a waterfilm from the backflow of wave run-up the shock pressures under real sea state conditions are damped more frequently (compared to those on vertical walls) and they are mixed with pressures from waves and wave run-up (Fig. 2).

In previous reports results with respect to the pressure peak values are primarily predominant, but as to be seen in Fig. 2, 3 and 4, it is often difficult to distinguish

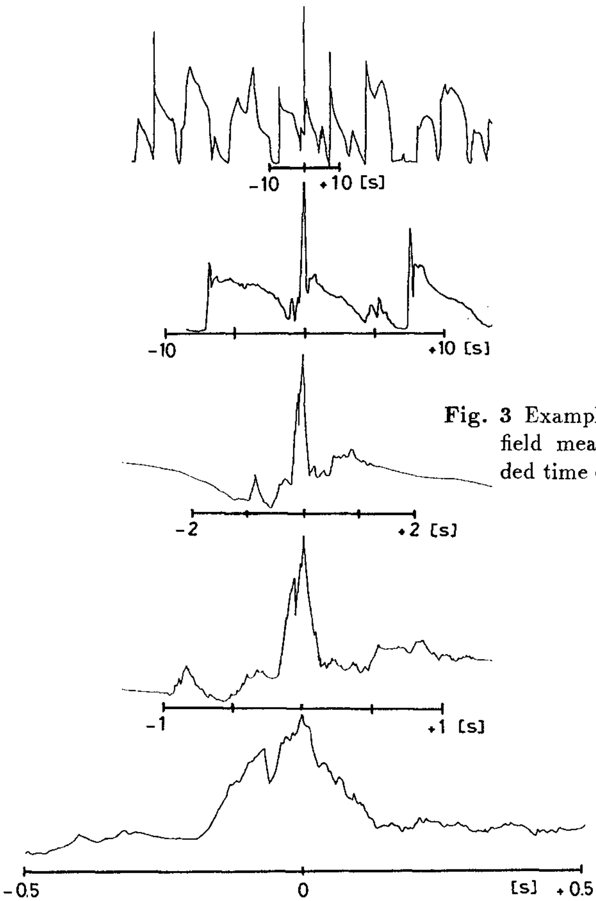


Fig. 3 Example of a record from field measurements with extended time disintegration

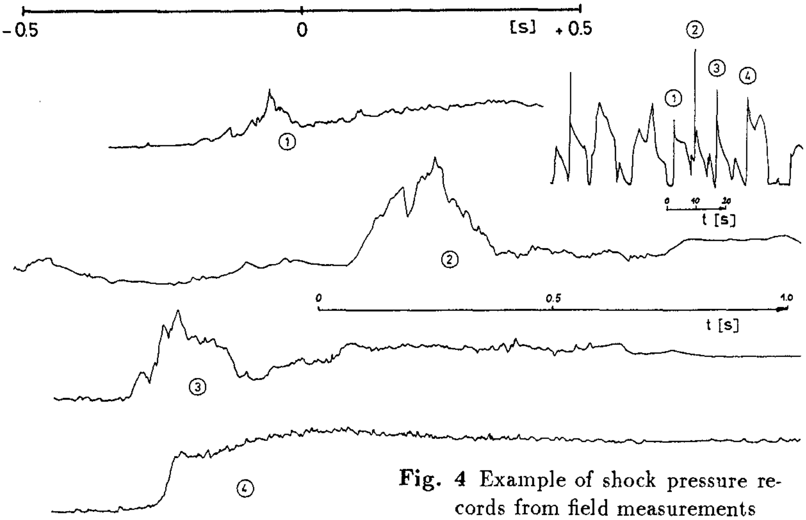


Fig. 4 Example of shock pressure records from field measurements

the real shock pressures from the steep wave fronts or the wave run-up fronts, using normal speed records. Furthermore a first review of some pressure-time histories from measured field data, which seem to fullfill classic shock pressure shapes on a normal speed record, pointed out a certain disagreement with common representations in former reports. This is illustrated in Fig. 3, where the time disintegration is extended in steps from top downwards up to 160 times. Fig. 4 demonstrates that even a series of four waves one by one produces four completely different pressure-time histories at same measuring point on the dyke surface.

Using normal speed records as shown in Fig. 2 for peak pressure analysis usually two main boundary conditions should be fullfilled to find out shock pressures:

1. the rising time up to the maximum peak pressure must be much shorter than the wave period (roughly less than 1/10 of the wave period).
2. the maximum peak value should exceed a certain multiple value of the wave height, that means a setting of a minimum value.

On the records as shown in Fig. 2, and on the top of Fig. 3 and 4 the first condition can be estimated only insufficiently. The second condition can result in neglecting real shock pressures with smaller peak values, but yet very short rising times, which might be important to the stability of seadykes. Furthermore the statistical values are affected by setting a minimum value.

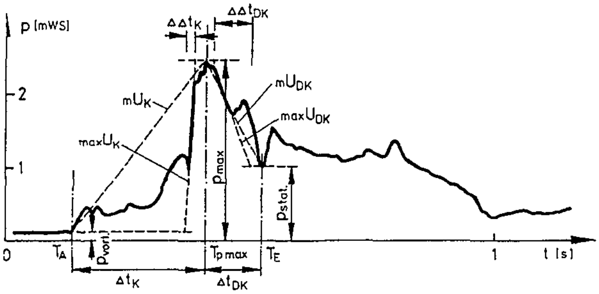


Fig. 5 Scheme for definition of shock pressure anatomy parameters

Table 1: List of shock pressure parameters

Symbol	Definition	Unit
p_{max}	total maximum (peak) pressure (at $T_{p\,max}$)	mWs (meter water column)
p_{vorl}	pressure before the occurence of a shock pressure (at T_A)	mWs (meter water column)
p_{stat}	minimum pressure between the decompression term and the quasi-static term (at T_E)	mWs (meter water column)
T_A	starting time of shock pressure	s (*second*)
$T_{p\,max}$	time at maximum pressure	s (*second*)
T_E	starting time of the quasi-static term	s (*second*)
Δt_k	total rising time of compression term, related to: $(p_{max} - p_{vorl})$	s (*second*)
$\Delta\Delta t_k$	minimum significant rising time of compression term, related to $(p_{max} - p_{vorl})$	s (*second*)
Δt_{ph}	time period to maximum pressure (at $T_{p\,max}$), related to the first $T_{p\,max}$ of all pressure cells	s (*second*)
mU_k	mean rising velocity, related to Δt_k and $(p_{max} - p_{vorl})$	mWs/s (meter water column per second)
$max\ U_k$	maximum significant rising velocity, related to $\Delta\Delta t_k$ and $(p_{max} - p_{vorl})$	mWs/s (meter water column per second)

More detailed information on shock pressures ("anatomy") can be obtained from high speed recorded pressure-time histories as shown in Fig. 3 and 4. To distinguish all these completely different pressure-time histories and to get a certain generalization, these complex shapes may be described suitable by parameters as shown in Fig. 5. The parameters in this example of a pressure-time history are seperated for compression time (index K) and decompression time (index DK). The anatomy parameters, used in this paper, are listed in Table 1. It must be remarked, that in chapter 4.1 the peak pressure values p_{max} from Table 1 are defined as p.

An example of time-pressure histories of one individual wave event, recorded at WANGEROOGE location, is shown in Fig. 6. The local distribution of the anatomy parameters, determined from these pressure-time histories as listed in Table 1, are plotted in Fig. 7 in dependence of the waveheight related distance $\Delta d/H_{1/3}$ from stillwaterlevel. It should be noted that the recorded pressure-time histories mostly have more chaotic shapes than the classic ones in Fig. 6. More aspects on analyzing high speed recorded pressure-time histories are reported by Grüne, (1988).

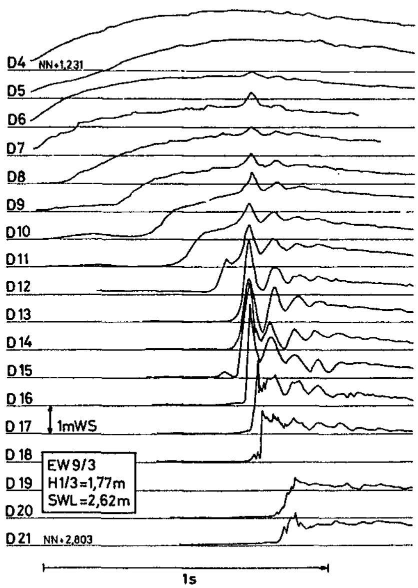


Fig. 6 Pressure-time histories for an individual breaking wave

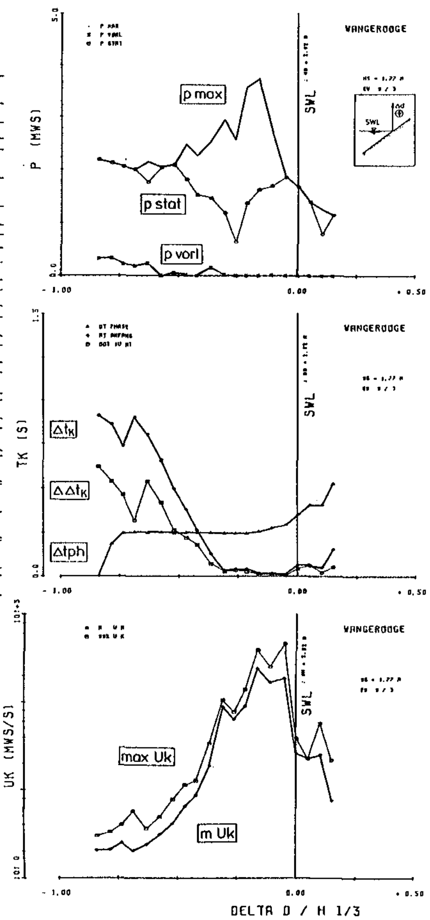


Fig. 7 Local distibution of anatomy parameters from the pressure-time histories in Fig. 6

4. RESULTS

The results, described in this paper, are analyzed from normal speed records (EIDERDAMM and WANGEROOGE location) with respect to peak pressure values as well as from high speed records (WANGEROOGE location) with respect to the anatomy of shock pressures.

4.1 Results of peak pressure values and their local distribution

Although the analysis of peak pressure values from normal speed records does not not give detailed information on shock pressure characteristics as mentioned before, this method is usefull to find the limited area of "worst case overall occurrence" of shock pressures on slopes, especially with respect to the local distribution.

An example of peak pressure data for one time interval, measured at Eiderdamm location on slopes 1 : 4, is given in Fig. 8. On the vertical axis, the statistical peak pressure values, which are determined directly from the peak pressure data, are related to significant wave height $H_{1/3}$. NP/NW gives the ratio of peak pressures to the number of individual waves (related frequency of occurence). The horizontal axis gives the local distribution on the slope as a vertical waveheight related distance from the mean stillwaterlevel $\Delta d/H_{1/3}$ of the time interval. The data of the different pressure cells are used to form an linear interpolated envelope curve.

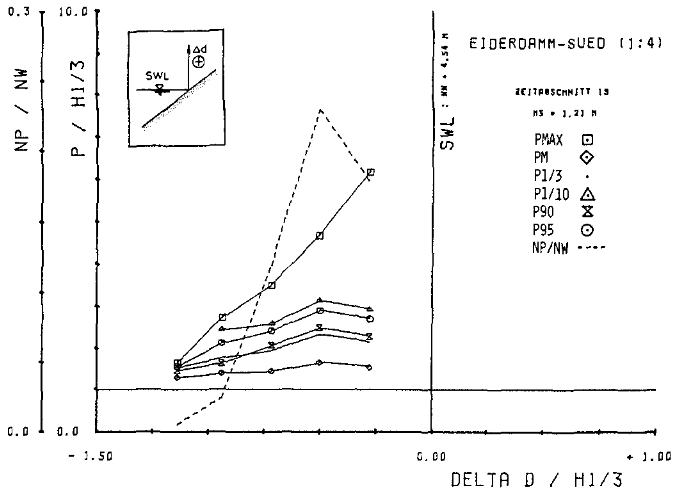


Fig. 8 Example of peak pressure data measured on slope 1 : 4 at EIDERDAMM location for one time interval

It must be remarked, that such summarized distributions of peak pressure values are influenced

first by the measuring time, which is restricted for field measurements due to changing of stillwaterlevel

second by the location of the pressure cells on the dyke referred to stillwaterlevel during storm surge events

third by the distance of pressure cells from each to another, which gives the local disintegration of the envelope curves.

Some further remarks should be made on statistical parameters, evaluated from calculated lognormal distribution. As shown in Fig. 9, the lognormal distribution of peak pressure values, measured with 23 pressure cells on the total dyke surface for one time interval, can be fitted by a least square method calculated lognormal distribution only moderate. It must be mentioned that this time interval has a length of 80 minutes with closely constant stillwaterlevel and significant wave height, which is rather rare for measurements during storm surge events.

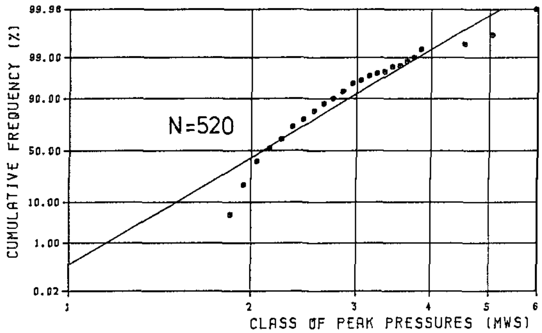


Fig. 9 Example of lognormal distribution of peak pressure values for one measured time interval

The local distributions of the statistical peak pressure parameters, evaluated from calculated lognormal distribution and related to mean peak pressure values, are plotted in the upper part of Fig. 10. It is obvious, that these parameters vary in dependance of the distance to stillwaterlevel. The local distributions of the waveheight related statistical parameters determined directly from the peak pressure values for this time interval are plotted in the lower part of Fig. 10. It is conspicious, that the measured maximum peak pressures form the statistical values extensively and that they agree quite well with the corresponding calculated values $p_{99.9}$. This comes out more clearly in Fig. 11, where for each measured time interval at Wangerooge location the calculated statistical values $p_{99.9}$ from all shock pressures are plotted versus the measured maximum ones. Due to these results and additionally due to the fact, that the time for measuring shock pressures during storm surge events in field with nearly constant stillwaterlevel and waveheight parameters is limited, the measured maximum peak pressure values have been favoured for further considerations instead of calculated statistical values.

To get the "worst case occurrence area" with a certain approach to accuracy, the envelope curves for p_{max} of the different measured time intervals are superimposed to a summarized envelope curve, which is shown in Fig. 12 as an example for one storm surge event. For the same storm surge event the summarized envelope curves of the different statistical parameters are plotted in Fig. 13. It can be seen clearly, that the occurrence area spread over a wide range on the slope, but the intensity varies considerable in relation to distance from stillwaterlevel.

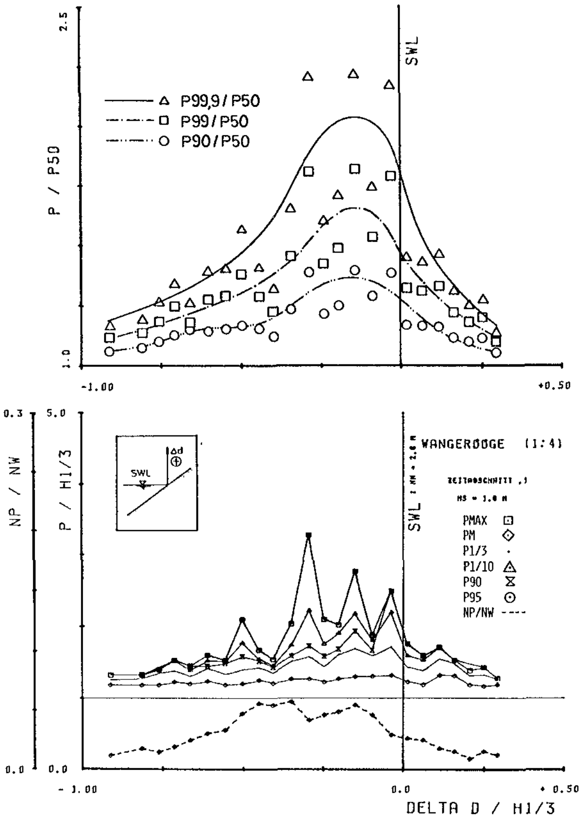


Fig. 10 Example of local distribution of statistical peak pressure values for one measured time interval

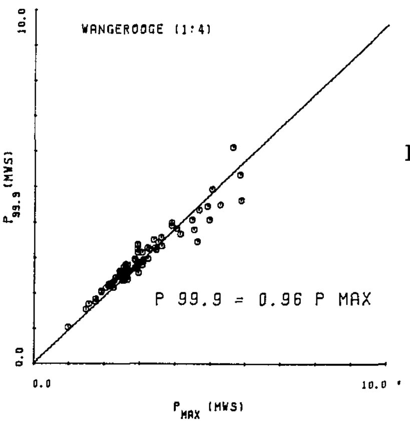


Fig. 11 Relation between statistical parameters $p_{99.9}$ and measured maximum pressure p_{max} for different time intervals, measured at WANGEROOGE location

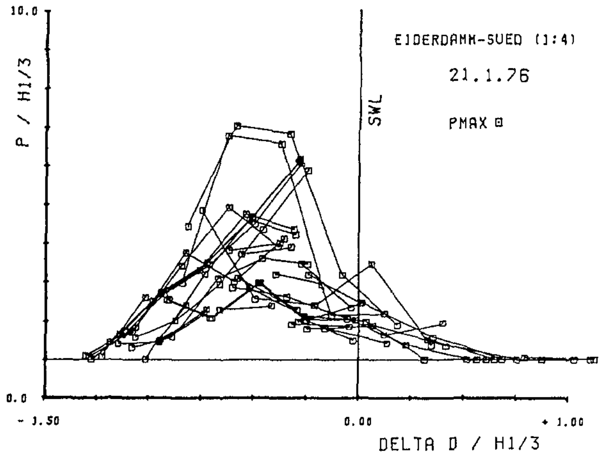


Fig. 12 Superimposed envelope curves for p_{max} of different time intervals, measured during one storm surge event at EIDERDAMM location 1 : 4

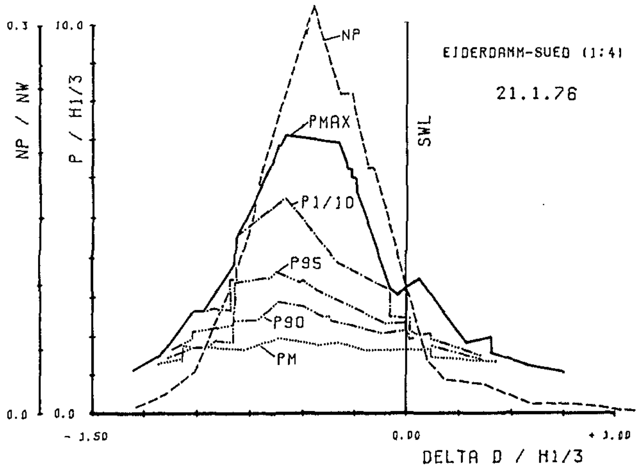


Fig. 13 Summerized envelope curves for different statistical parameters, measured during one storm surge event at EIDERDAMM location 1 : 4

The envelope curves for some parameters from all measured storm surge events at Eiderdamm location are compared in Fig. 14 for the both slopes 1:4 and 1:6. There is no significant difference of the total area of occurrence and of the mean pressure distribution between both slopes, but frequencies of occurrence and maximum peak pressures are lower on slope 1:6 due to the different wavebreaking and wave run-up characteristics.

A comparison of the peak pressure data between the two different locations with same slope 1:4 is given in Fig. 15. The total area of shock pressure occurrence is closely identical for both locations just as the mean pressure value distributions,

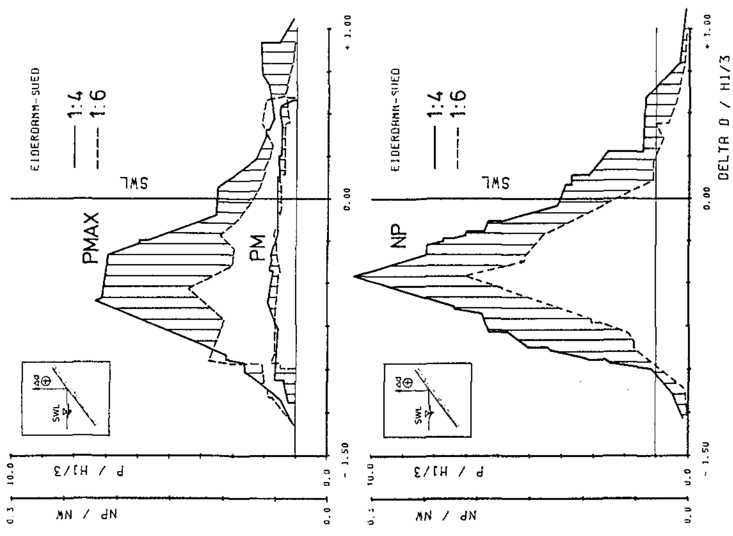


Fig. 14 Comparison of peak pressure parameters and their local distribution between 1 : 4 and 1 : 6 slope at EIDERDAMM location

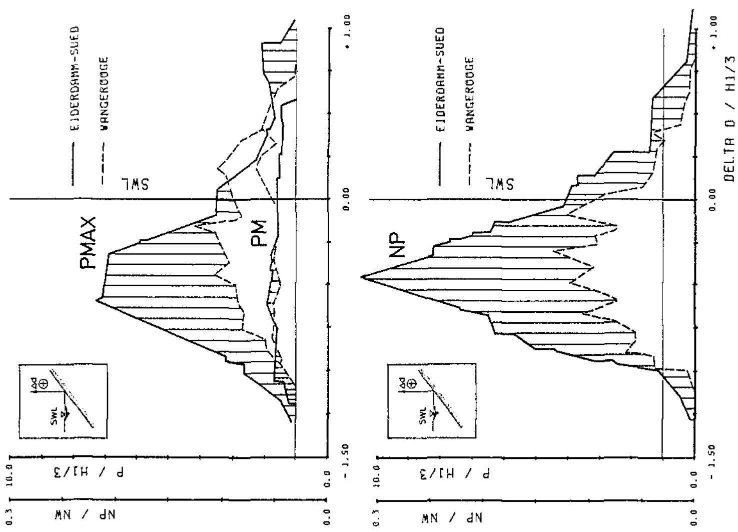


Fig. 15 Comparison of peak pressure parameters and their local distribution for slope 1 : 4 between the EIDERDAMM and WANGEROOGE location

but considerable differences occur for maximum peak pressure values and for the frequency. This is doubtless the influence of the different characteristic of local wave climate at both locations. Due to different waterdepth to waveheight relations in front of the slopes the plunger breaker type is predominant at Eiderdamm location, whereas at Wangerooge location the spilling breaker type is predominant. It should be noted, that similar effects from the wave characteristics were found also for wave run-up data, measured at both locations (Grüne, 1982).

4.2 Results of pressure-time history parameters (Anatomy parameters)

The results of parameters, evaluated from pressure-time histories as described in chapter 3, indicate very clearly, especially with respect to local distribution, that a certain gliding transition exists from the characteristics of steep wave front to those of shock pressure and then again to those of run-up front (see Fig. 7). This can be confirmed by the relations between some parameters independently from local distribution. Due to restricted place in this paper the following plots only should give an first overview of some summarized pressure-time history parameters from one storm surge event.

The relation between p_{vorl}, which represents the thickness of watersheet before shock pressure occurrence, and peak pressure values p_{max} is given in Fig. 16. The solid line gives the upper limit of peak pressures with respect to watersheet thickness and indicate the damping effect of a possible watersheet from the backflow of the preceeding wave. The mean rising time Δt_k is plotted versus the peak pressure value p_{max} in Fig. 17. The solid line represents the upper limit of the longest measured rising times, which decrease with increasing peak pressure values.

Fig. 18 gives the local distribution of the peak pressure values p_{max}. There is in fact no distinct tendency, but a broad spreading around stillwaterlevel. There is a clear tendency for the local distribution of the watersheet thickness p_{vorl} in Fig. 19; the upper limit of the thickness decrease at higher levels on the surface. All data give an impression of the numberless different shapes of pressure-time histories.

A generalized scheme for the local distribution of the pressure-time history parameters is shown in Fig. 20. This scheme is a first evaluation from a part of analyzed individual wave events. These generalized shapes were found more or less exactly for all investigated significant shock pressure events, which indicates a certain deterministic characteristic of wave-induced pressures on slopes. The shapes may be roughly classified into five different local domains (circled in Fig. 20) with different trends (listed in the table):

- the first one represents the approaching steeped wave front
- at the second domain the steeped wave front has its maximum height, this can be seen as the breaker point
- the third domain represents the area between the breaking wave front and the point, where the breaker tongue hits on the dyke surface. In this area the most chaotic pressure-time histories were found due to the enclosed air pockets with high turbulence
- the fourth one represents the area, where the breaker tongue hits on the dyke surface and where significant shock pressures with classic shapes occur
- the fifth domain represents the very steep front of wave run-up.

It must be remarked, that due to definition these parameter-shapes do not represent the conditions at same time, therefore some further investigations were made to check the phase lag of these shapes. The results from these investigations indicated, that all maximum peak pressures can occur closely within a total time lag of 50 milliseconds, referred to the maximum peak pressure $max\, p_{max}$.

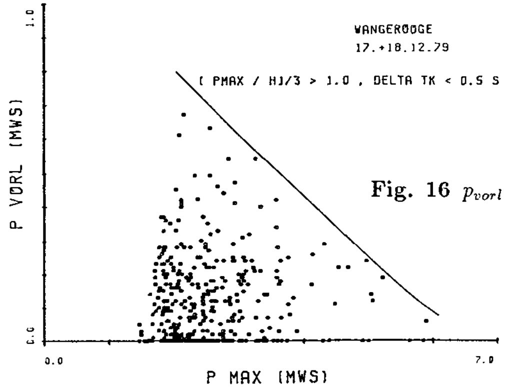


Fig. 16 p_{vorl} versus p_{max}

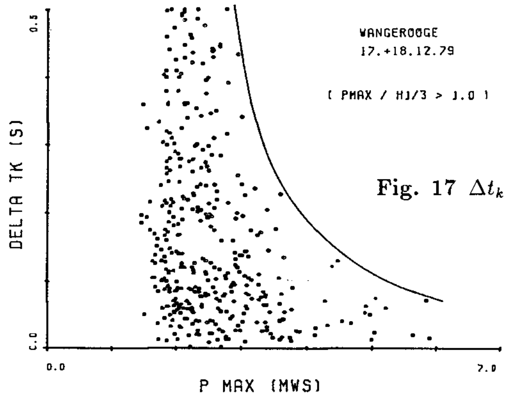


Fig. 17 Δt_k versus p_{max}

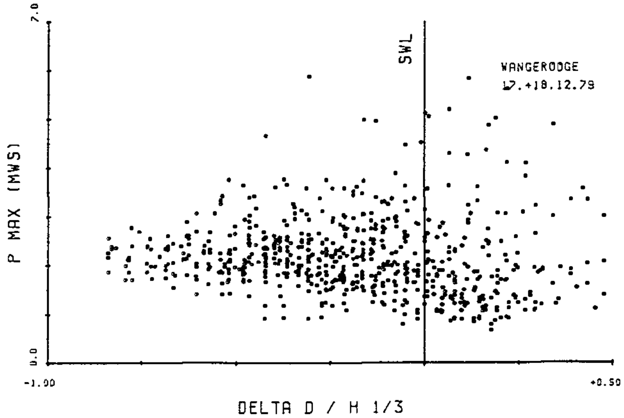


Fig. 18 Local distribution of p_{max}

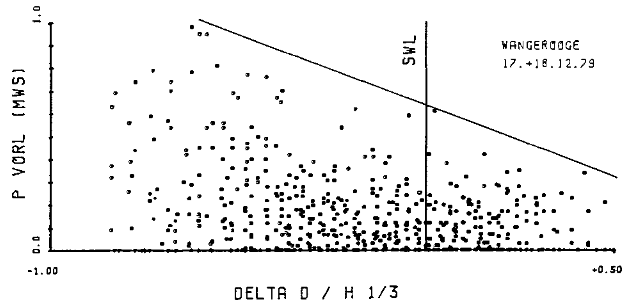
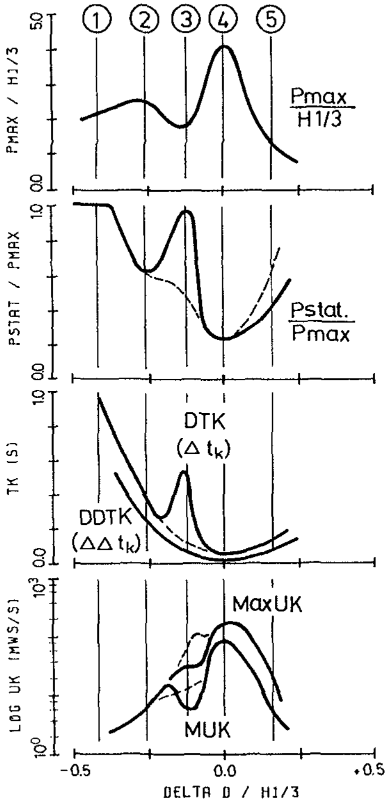


Fig. 19 Local distribution of p_{vorl}



	1	2	3	4	5
Pmax / H1/3	<max	<max	≪max →min	max	≪max min
Pstat. / Pmax	1	<1	→1 (<1)	≪1 min	→1
DTK (Δ tk)	≫0	>0	>0 (≫0)	→0 min	>0
DDTK (ΔΔ tk)	≫0	>0	>0	→0 min	>0
MaxUK MUK	min	>min ≪max	<max	max	<max
MaxUK / MUK	→1	>1 (≫1)	>1	→1	→1

Fig. 20 Generalized scheme for local distribution of anatomy parameters

This leads to the first assumption, that anatomy parameter shapes, such as shown before, can give a realistic approximation of the synchronous worst-case loadings from individual breaking waves. Such a worst-case loading model for the synchronous pressure distribution is shown in Fig. 21. The thick line is evaluated from a part of the data from WANGEROOGE location. The thin line is extrapolated to the maximum peak pressure values measured at EIDERDAMM location. The local distribution is related to the true length on the surface with zeropoint at the maximum peak pressure. It must be mentioned, that this zeropoint varies considerable with respect to distance from stillwaterlevel as shown in Fig. 19. For application this loading model may be used as an input to a numerical model, to investigate for example the bending moments of an cover layer or the penetration of shock pressures into sandcore. To get the worst case, for different applications the following parameters of the loading model in Fig. 21 should be varied systematically with certain ranges:

- the waveheight related peak pressure $max\, p_{max}$ up to 10

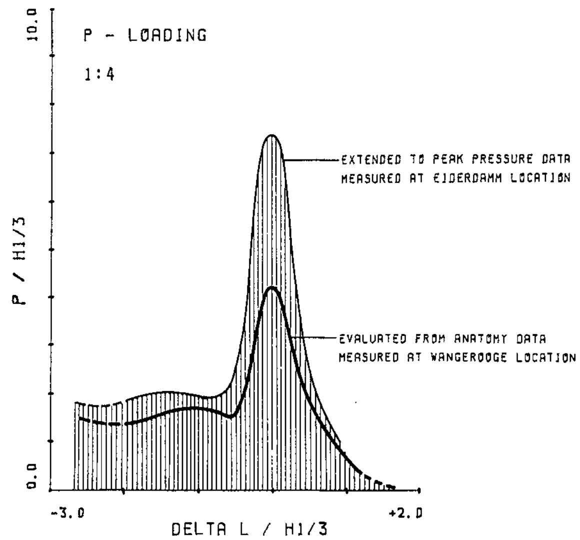


Fig. 21 Worst-case loading model (local peak pressure distribution)

- the duration time from $10ms$ up to $200ms$
- the waveheight related vertical distance from stillwaterlevel of the local acting point of $max\, p_{max}$ from -0.75 up to $+0.5$

5. CONCLUSIONS

From the results of the measurements in field the following may be stated:

- The definition of shock pressures for field data, especially measured on slopes, is more complicated than for laboratory data with idealized boundary conditions.
- Analysis of peak pressure values from normal speed records are usefull to get the local distribution of shock pressure occurrence on dyke surface.
- Shock pressures occur on slope 1:4 and 1:6 roughly within the same area on the slope, but have different magnitudes of pressure and frequency.
- The breaker type has a substantial influence on the magnitude and frequency of shock pressures, which was also found for wave run-up data. Waves with predominant spilling breaker type generate fewer and smaller shock pressures compared to waves with predominant plunging breaker type.
- The results may be described statistically, most sufficiently with a lognormal distribution, nevertheless the related ratio of the lognormal distributed pressure parameters, for example $p_{99.9}/p_{50}$, varies in dependence of the distance

from stillwaterlevel. The measured maximum peak pressure values of limited time intervals are well represented by the parameter $p_{99.9}$ from lognormal distribution.

- It has been demonstrated, that for detailed statements on the occurrence of shock pressures and the related loads on dykes an analysis of high speed pressure-time histories measured in field and in full-scale laboratory under real sea state conditions is necessary. On slopes shock pressures are damped more frequently compared to vertical walls and mixed with the pressures from waves and wave run-up, especially under real sea state conditions. Therefore the pressure-time histories mostly have very complex shapes. These complex shapes can be described suitable by parameters. If the pressure-transducers cover the area on the surface with a certain disintegration, the local distributions of these parameters for individual waves can be used for a loading model.

The research program on shock pressures will be continued with respect on combining the field data with different small-scale and full-scale laboratory data, especially those, measured in the "LARGE WAVE CHANNEL OF University Hannover and Technical University Braunschweig" (Grüne, Führböter 1975, Führböter 1986, Führböter, Sparboom 1988).

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