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Experimental study on mechanism of sea-dike failure due to wave overtopping

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ABSTRACT

This work, which was largely a fruit of China's national marine hazard mitigation service, explicitly reveals the major mechanism of sea-dike failure during wave overtopping. A large group of wave-flume experiments were conducted for sea dikes with varying geometric characteristics and pavement types. The erosion and slide of the landward slope due to the combined effect of normal hit and great shear from overtopping flows was identified the major trigger of the destabilization of sea dikes. Once the intermittent hydrodynamic load and swash caused any deformation (bump or dent) of the pavement layer, pavement fractions (slabs or rubble) on the slope started to be initiated and removed by the water. The erosion of the landward slope was then gradually aggravated followed by entire failure within a couple of minutes. Hence, the competent velocity would be helpful evaluate the failure risk if as well accounted in standards or criteria. However, the dike top was measured experiencing the largest hydrodynamic pressure with a certain cap while the force on the wall increased rapidly as the overtopping intensity approached the dike-failure threshold. The faster increase of the force on the wall than on the landward slope yielded the sequencing of loads reaching hypothetic limits before failure as: dike top – top-mounted wall – landward slope. Therefore, beside the slide failure, the fatigue damage due to the instantaneous hydrodynamic impact might be another mechanism of the dike failure, which did not appear in the experiment but should be kept in mind. Instead of the widely adopted tolerable overtopping rate, a 0.117–0.424 $m^3/(m\,s)$ range of overtopping discharge and a 10 m/s overtopping velocity for the failure risk of typical sea dikes along China's coastlines were suggested, which enables the possible failure risk prediction through empirical calculations. The failure overtopping rate was identified strongly dependent on the pavement material, the landward slope and the dike-mounted wall but showed little variation with the width of the dike top. The flat concrete pavement and gentle landward slopes are suggested for the dike design and construction. For given configurations and hydrodynamic conditions in the experiment, the dike without the wall experienced less overtopping volume than those with the 1-m top-mounted wall. Meanwhile, the remove of the wall increased the failure overtopping rate, which means a certain increase of the failure criterion. Thus, care must be taken to conclude that the dike-mounted wall seems not an entirely appropriate reinforcement for the stability and safety of coastal protections. This should be further checked and discussed by researchers and engineers in the future.

1. Introduction

Coastal protections against extreme marine events are important for the safety of infrastructures, properties and populations. Seventy percent of China's coastlines are protected by artificial sea dikes, seawalls, breakwaters, and groins. A certain amount of them were damage, breached, or even entirely destructed during previous marine hazards. This was quite a common concern in Europe, United States, and many other regions. The performance of protection structures largely depends on both their construction characteristics and the hydrodynamic condition. Instead of accounting various factors such as wave, tide, surge and structures'

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geometric conditions, the wave overtopping process is considered as an integrated hydrodynamic response to the combination of all these complex factors. Excessive amount and intensity of wave overtopping could cause failure of coastal protections, property losses, and casualties. Reliable assessment of wave overtopping and thorough understanding of the mechanism of sea-dike failure has been a critical desire for safety design of coastal defenses.

Wave overtopping research has been of great interest and experienced a significant progress during past three decades [48,1,3,41]. The tolerable overtopping limit is commonly used for coastal risk control. Therefore, the research work was mostly focused on assessment methods and databases of overtopping rates [51,17,22,56,42,12], which are very useful to understand and predict the wave overtopping phenomenon. These methods can be basically grouped into three types: empirically parameterized formulas, numerical models, and physical experiments. In respect of performance, they heavily depend on each other therefore are occasionally adopted as complementary tools.

Empirical formulations have been derived and improved based on experimental data or field measurements [37,18,15,52]. Dominating variables of both wave and structure are parameterized and fitted to the collected data. Most formulations for either sloping or vertical sea-wall feature exponential functions of the freeboard for the dimensionless overtopping rate. Earlier, the formulas was applicable to restricted structure types with specific structure configurations but still proved to be quite useful. Later, groups of researchers used various methods to improve the accuracy and the application range based on previous equations, by increasing the number of parameters and complexity of equations. Meanwhile, a set of so-called artificial neural network (ANN) methods were proposed and applicable to a broad range of structure geometry at the cost of multi-regression between inputs and outputs [53–55,57]. Still, all of above equations are relatively straightforward for the wave overtopping assessment.

As the modern computing power progressed, the numerical modelling of wave overtopping has become a sophisticated approach for much more complex setups and water-structure interaction [11,21,19,28,47,43,33,30]. Detailed surface deformation, velocities, and non-hydrostatic pressure could be computed from many sets of simulations with the varying bathymetric and hydrodynamic conditions. Instead of regular or narrow-banded spectra, numerical models are able to simulate a broad range of wave spectra if they are mathematically specified. There are three most common types of models adopted: (1) nonlinear shallow water equation based models (NSWE); (2) phase-resolving models [24,58,59,49]; (3) full 3D Navier–Stokes solvers [31,45,8]. The computational cost and accuracy increase as the approximation level goes up. The NSWE has the lowest approximation level with the highest efficiency. Its fast computing is very useful at statistic analysis of long-duration wave overtopping events. However, severe limitations to the accuracy inherent in the depth averaging and hydrostatic pressure hinder detailed investigations into the wave overtopping process. The wetting-drying boundary, the empirical wave breaking method and the single surface assumption are also significant restrictions to real-world applications. The most popular phase-resolving model, Boussinesq, maintains the balance between accuracy and efficiency. Nonhydrostatic characteristics and higher order approximation levels result in quite satisfactory results [61,10,62]. Still, the single surface assumption limits the accuracy in smaller scale when bubbles and multi-interface get involved. Full 3D Navier–Stokes solvers are all about small-scale modelling. The plunging, spilling, vortex, turbulence, and air–water interaction over the structure during the overtopping process might be modeled impressively close to reality while the computational cost would be extremely high.

Both empirical mathematic formulas and numerical models rely heavily on the experimental validation. Thus, the physical models plays an indispensable role in the wave overtopping assessment [25,50,2,16]. Usually scaled experiments are carried out in either wave flumes or wave basins. The hydrodynamic properties are observed and measured. The combination of different factors such as waves, winds, and the structure porosity, which are mathematically difficulty to approximate, could be addressed fairly well. Reliable data can be collected for further detailed analysis. However, the wave generation is limited to simple wave conditions or narrow banded spectra. The scale effect and measurement errors are more or less inevitable. Besides, the cost of the experimental model is distinctly higher than previous two types of methods especially when carrying out studies for a large number of varying setups.

In any case, some aspects have reached apparent limits. Although the wave overtopping issue has progressed significantly, the sea dike failure research is lag behind and generally case specific such as for tsunami [23]. Some time-dependent empirical formulations predicting the risk of coastal structural failures due to the increased wave overtopping have very limited application range [29,13,9]. Numerical and experimental models have been applied to the dam failure due to the overtopping by coupling a fluid dynamic model for the simulation of the free surface and through-flow problems together with a numerical technique for the calculation of the structural response and deformation [34,26,44]. However, majority of these studies are limited to the homogeneous embankment dam filled with either earth or rubbles with few modern construction features such as pavement layer or dike-mounted wall [7,38,27]. Previous studies were mainly focused on widely adopted tolerable overtopping rates [39,36,20]. Usually the destruction happens during severe wave overtopping processes. Few research has been focused on the protection structure's failure risk under the overtopping while most studies take unitary account of tolerable overtopping discharge assuming the protection structure's integrity. The thickness, shear velocities, and pressure of the overtopping water have direct implications for the destabilization and failure of the sea dike therefore should receive more attention [46,35,4,5]. This work explicitly presented the mechanism of the water-structure interaction and the sea-dike failure process due to wave overtopping through extensive experiments. Failure overtopping limits of typical sea dikes along China's coastlines were suggested, which enables the possible failure risk prediction by the empirical calculation of case-specified overtopping rates. Probable affecting parameters such as geometric characteristics, pavement types, and dike-mounted walls have been quantitatively investigated. Hydrodynamic loads were measured by densely distributed pressure sensors on the pavement surface of the dike model. Measured experimental data could provide the basis of further empirical-formula-based and numerical investigations for a broader range of wave spectra. The study results would be useful to engineers and planners who work on coastal communities that will withstand future marine hazards.

2. Experiment

The increased water depth during the hurricane surge + tide enables large waves propagating very close to the sea dike front before considerable dissipation. Especially low-frequency long waves featuring infragravity time scales are more penetrable and energetic [6]. Intensive wave overtopping would largely threaten the safety of the sea dike during extreme marine events. Due to the wave-dike interaction in the front, the hydrodynamic process of wave overtopping becomes very complex. Records of damaged but not entirely breached sea dikes show that the top and landward