CHAPTER 131

TSUNAMI HAZARD AND DESIGN OF COASTAL STRUCTURES

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Abstract

Damage of coastal structures by tsunamis results by the direct and indirect action of hydrostatic and dynamic pressures, foundation failures, overtopping and flooding. Reliable assessment of the potential tsunami hazard at a coastal site and adequate engineering design of critical structures require analysis and understanding of all aspects of a tsunami system leading to its terminal behavior. Description of the space-time history of tsunami waves generated by impulsive disturbances require consideration of events and processes in the following regimes: (a) generation; (b) propagation and dispersion; and (c) termination. Processes and events in each regime during the development of a tsunami are under their own unique hydrodynamic constraints but are dependent on what has preceeded. In predicting tsunami wave characteristics at some distance from the generating source, the error structure may be pyramidal. Essential to any method of tsunami prediction at a distant or a nearby coast will be the full consideration and study of tsunami generative mechanisms. If the tsunami generation mechanics cannot be deduced with a reasonable degree of accuracy, it is not likely that the tsunami terminal aspects will be reliably predicted. Prediction of tsunami height at a distant or at a nearby coast requires knowledge of the magnitude and type of ground displacements in the tsunami generating area and of the characteristics of the surface waves resulting from such action. Although all mechanisms involved during tsunami generation are not fully understood, it is possible to obtain a suitable tsunami initiating function through the use of experimental data, historical data, and established empirical relationships, for each type of generating mechanism. Reliable computation of the tsunami propagation effects over and across the ocean can be obtained with proper modeling to provide an adequate description of the tsunami energy flow through the use of physical and numerical studies. Similarly, the terminal aspects and nearshore modification of the tsunami wave system can be approximated to provide the engineering criteria necessary for the assessment of the potential tsunami hazard at a coastal site.

Introduction

Increasing pressure for the construction of large coastal installations, such as power plants, and superport terminals, and the increasing residential development of coastal zones, have emphasized recently the need for more accurate estimates of the terminal effects of tsunamis. Questions that most often arise deal with such subjects as the frequency of catastrophic tsunamis at a given coastline; the maximum expected runup from a tsunami for a given site; the dynamic forces that can be expected; and finally how to design structures to withstand the forces and effects of a possible tsunami.

The answers are not simple. Attempts to solve these problems may become involved in numerous complex mathematical solutions which require numerous approximations and simplifications, to the point that the accuracy of these solutions becomes doubtful. In addition, theoretical and analytical solutions often assume a smooth transmission of tsunamis to the coast without taking into account the effects of obstacles (islands, seamounts, reefs, etc.) which complicate the phenomenon. At the mouths of rivers, in estuaries, and generally in bays or other irregular coastlines, tsunamis undergo such alterations and changes of their characteristics, that theoretical appraisal of tsunami height, runup, velocities, or forces on coastal structures often are invalid. In such instances, historical and statistical data, visual observations, and other empirically-derived data become the sole guide in evaluating the maximum possible height, runup, and effect of tsunami waves on coastal structures.

Unfortunately, historical and statistical data on tsunamis is nonexistent for certain coasts, or the historic record may be of very short duration to permit a suitable analysis. Therefore, there is always the danger in designing coastal structures that potential tsunami effects may be either ignored, underestimated, or overestimated. If the tsunami potential danger is underestimated or ignored, the design of the coastal structure will not be adequate. If the tsunami potential danger is overestimated, overdesign of the coastal structure results, causing excessive financial expenditure for the project. In spite of all these difficulties, a combination of historical observations, laboratory experiments, and theoretical studies, provide assurances of a more accurate evaluation of a probable maximum tsunami at the coast. Such studies require time and expenditures which cannot be reasonably justified unless the coastal structures are important and will serve a critical function (i.e., protection of nuclear power plant).

Interaction of Tsunamis with Coastal Structures: Damage of coastal structures by tsunamis may be by the direct action of hydrostatic and dynamic pressures on the face of a structure, resulting in foundation failure due to erosion, or overtopping and flooding. The forces on the face of the structure are caused by the rapid water motion in the form of gravity waves or in the form of irregular violent motions. The hydrostatic and dynamic pressures of gravity waves on structures depend basically on the height, direction, period, and velocity of the waves, the design of the coastal structure, and a number of other factors.

The most adverse interaction of tsunamis with a coastal structure exists when the directional approach of the waves is perpendicular to the longitudinal axis of the structure because the pressure is exercised in the direction of least resistance of the structure. However, this is true if we consider only the water pressures on the structure and not other direct or indirect effects of a tsunami, which could be of greater danger, regardless of direction, or height. For example, there could be instances when the direction of water movement may not be perpendicular to the longitudinal axis of the structure and yet the water motion may result in strong currents which may undermine the structure by eroding the material near its foundation with subsequent failure.

The period of the tsunami is another factor which could influence the effect of these waves on a coastal structure. This may affect degree of flooding and permissible overtopping. Tsunami period is usually of 15-30 minute duration. Therefore, it is expected that when a tsunami arrives at an open harbor, it floods progressively both the outer and inner sides of coastal protective works of the harbor, without causing significant pressure differentials on opposite sides of structures. A small pressure differential on the two sides of a coastal protective structure may occur at the arrival of the tsunami waves due to the dynamic momentum of the moving water. This pressure effect is a function of the velocity of the tsunami and will be more pronounced if the harbor has a narrow entrance, if the tsunami approaches at high speeds, or if a bore is formed.

Hydrodynamic Pressures of Local Earthquakes on Coastal Structures: The design of coastal structures usually requires consideration of different loads which include those caused by wind waves, the weight of the structure itself, the seismic forces acting on the structure, and the permanent or moving loads resting or interacting with the structure. Although the seismic effects are often adequately considered, the hydrodynamic forces which could develop in the water from an earthquake and which interact with the structures, are often ignored.

Seismically-generated hydrodynamic pressures acting with a sloping breakwater, for example, are directly related to seismic accelerations, the depth of the water in front of the structure, and the slope of the structure's face. During a local earthquake, the hydrodynamic pressure on the structure ranges alternately from zero to a maximum value on both sides of the structure. It has an alternating direction in phase always with the direction of the seismic ground accelerations. It can be concluded that considerable hydrodynamic pressures can develop on the faces of coastal structures during a local earthquake and such forces should be considered in the design. These forces will be particularly critical in the design of high breakwaters, or of structures with a vertical face, if these structures will be constructed in areas where large and frequent earthquakes occur. A local earthquake may result also in oscillations of the waters of a bay or a harbor which could excite the natural mode of oscillation of a basin resulting in greater runup and damage to coastal structures within that basin. Such resonance effects are not always adequately considered in designing coastal protective works.

Engineering Guidelines

Runup height, terminal velocity and periodicity are the three most important terminal parameters of a tsunami of concern to engineers in designing coastal structures. Tsunami runup height and terminal velocity are the most difficult to estimate without knowledge of what has preceeded. For a complete understanding of the problem and for the development of the spacetime history of tsunami waves generated by impulsive disturbances, consideration should be given to events and processes in the regimes of generation, propagation and termination. Processes and events in each regime during the development of a tsunami are under their own unique hydrodynamic constraints but are dependent on what has preceeded.

Tsunami Generation: Prediction of tsunami height at a given coastal site requires knowledge of the magnitude and type of ground displacements in the tsunami generating area and of the characteristics of the surface water waves resulting from such action. Understanding of the disturbances responsible for tsunami generation is limited. Very little work has been done in relating tectonic or other impulsive disturbances to ocean surface effects. Most of the laboratory studies completed to date have investigated tsunamis resulting from simplified displacements under restrictions of analytical conditions which bear limited resemblance to processes in nature.

Although all mechanisms involved during tsunami generation are not fully understood, it is possible to obtain a suitable tsunami initiating function through the use of experimental data, historical data, and established empirical relationships for each type of tsunami generating mechanism. For example, the type and extent of crustal displacements associated with tsunamigenic earthquakes can be approximated. These displacements will depend on earthquake magnitude, depth of focus, epicenter location, geologic trends in the area, length of rupture, orientation, and type of ground motions.

In evaluating the runup at a specific coastal site, or the safety of a critical coastal structure (i.e. a nuclear power plant) for a tsunami generated from a distant or a local earthquake, consideration should be given to the nature, characteristics, and mechanism of the largest possible seismic event that can give rise to a maximum tsunami. It is proposed that the term of Maximum Probable Tsunami (MPT) be adopted in designating such a source event, and that criteria be developed to describe such design tsunami.

In planning or designing important coastal structures teleseismic and potentially tsunamigenic source areas should be identified geographically in relation to the site of interest. Tectonic structures and trends of each region should be identified. Historic information should be provided on depth, frequency, density, distribution, and magnitude of earthquakes, together with records of tsunami generating activity for each potentially tsunamigenic region. Following preliminary assessment of such data, a tsunamigenic source should be selected which would be most critical to the site of interest. Conservative values of seismic parameters should be assigned to a hypothetical earthquake which can produce the maximum initial tsunami function. For example, a magnitude of 8.5 on the Richter Scale may be assigned to a hypothetical, shallow-focus earthquake, having a rupture of 1,000 km, a total displacement area of 150,000 square kms, involving vertical displacements along the rupture of at least 3 meters, and having a critical orientation towards the proposed site.

Using critical seismic parameters of the source, empirical relationships, current theories, and other historic or experimental data, an initial tsunami function should be reasonably developed which should be consistent with ground displacements, coupling mechanisms, and source dimensions.

Tsunami Propagation: The initial tsunami wave and subsequent waves should be propagated from the source taking into consideration interactions, resonances, and boundary modifications, in order to obtain the maximum possible tsunami runup at site of interest.

Finite difference numerical computer programs have been developed for the propagation of tsunami waves across the deep ocean to the edge of the continental shelf and have been used for verification using data of historical tsunamis (Wilson and Torum, 1964; Hwang and Divoky, 1970; Hwang, Butler and Divoky, 1972; Houston and Garcia, 1974). Such computer programs take into consideration the sphericity of the earth in solving the linearized long wave equation of motion and continuity. The finite difference methods permit uplift deformation of the water surface at the selected tsunami source to be used as an initial condition. A time history of water surface information conforming to the bathymetic features of the ocean, is propagated away from the source and a transfer function is provided at the edge of the continental shelf. To propagate a tsunami across the continental shelf, other analytical solutions of the linearized long wave equation have been developed. Although numerical models exist which can propagate tsunami wave across the shelf, the necessity for large systems and the computer storage and routine requirements are great and make such solutions expensive. Often simple two dimensional analytic solutions are used to propagate standing waves over the Continental shelf, based on theoretical solutions for tides in canals. These studies do not necessarily produce very correct results, but they are better than no studies at all.

Tsunami Termination: The probable maximum height of tsunamis at a coastline is difficult to estimate. There is no simple or exact method or numerical model which can be used for estimating tsunami runup. Most of the coastlines where tsunami runup estimates are required are irregular. Interactions of tsunami waves with an irregular coastline may result in the trapping and resonance of tsunami wave energy and may result in higher-than-expected runup. As mentioned earlier, large bays and harbors may have resonant periods which may coincide with the peak of the tsunami spectrum and such resonance could result in an increase of wave height and runup. Tsunami runup calculations for such irregular coastlines must first take into consideration the increase of wave height by resonance, then use this estimate as input in calculating total runup. Also, ambient conditions and cumulative effects should be considered. Numerical models applicable to runup estimates of long waves have been developed which can be valid for waves of the tsunami frequency. In using these models, care should be exercised in selecting the proper boundary conditions.

The water velocity of the tsunamis that flow into a coastal area is difficult to estimate because it depends on many such factors, as the topography, the direction of approach, and the length of the waves. Because of the complexity of flow conditions, the velocity of the water can only be roughly approximated. An erroneous assumption often used in estimating terminal velocity is treating the tsunami as a bore -- something which in reality does not occur frequently.

Finally, since all the factors which contribute to tsunami runup are not fully understood, tsunami inundation cannot be computed entirely from theoretical analysis. For coastlines where historical information on runup is available, a statistical approach can be used to predict future events. This method does not require a complete understanding of the hydrodynamic considerations involved, but examines the magnitude and frequency of occurrence of historical tsunami runup. Such frequency analysis has been commonly used for the study of rainfall and stream flow records (Foster, 1935). Gumbel, (1941, 1942) applied an extreme value probability distribution to flood flows. Similar frequency studies of extreme events have been made ranging from rainfall to floods, to drought, to water quality and to ocean wave studies. In general, frequency analysis is a useful analytic tool for the study of randomly occurring events, such as large tsunamis.

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