equal to the mean of the heights of the highest one-third waves in a wave group, as representative of a particular sea state. Therefore, the significant wave concept was based upon the understanding of sea waves as a random process. However, the significant wave, expressed in terms of a single wave height and wave period, is sometimes misunderstood by engineers to represent waves of constant height and period. The theory of monochromatic waves and experimental results obtained from a train of regular waves have been directly applied to prototype problems in the real sea on the belief that the regular waves correspond exactly to the significant wave.

As early as in 1952, a group of American oceanographers, headed by Pierson,[5] took the first step in recognizing the irregularity of ocean waves as a fundamental property and incorporating this fact in the design process. The so-called P-N-J method[6] of wave forecasting, often compared with the S-M-B method, introduced the concept of wave spectrum as the basic tool for describing wave irregularity. The generation and development of wind waves, the propagation of swell and wave transformation near the shore were all explained in detail via the concept of wave spectrum. Although the spectral concept became widespread among oceanographers at an early stage, coastal and harbor engineers with the exception of a few researchers considered it too complicated. Hence, the introduction of spectral computation techniques into the design process for coastal structures was much delayed.

With advances in wave studies, however, engineers have gradually become aware of the importance of wave irregularity and its relevance in engineering applications. It has been demonstrated many times that the use of regular waves with height and period equal to those of significant wave can give inconsistent or erroneous results in the analysis of wave transformation and action of waves. Therefore, in this book, the concept of randomness in waves is taken as fundamental in the design procedures concerning waves in the sea. A total system of procedures for designing maritime structures against random sea waves is presented.

1.2 Outline of Design Procedures against Random Sea Waves

1.2.1 *Wave Transformation*

A prerequisite for the reliable estimation of waves on maritime structures is a detailed understanding of how waves transform during their propagation

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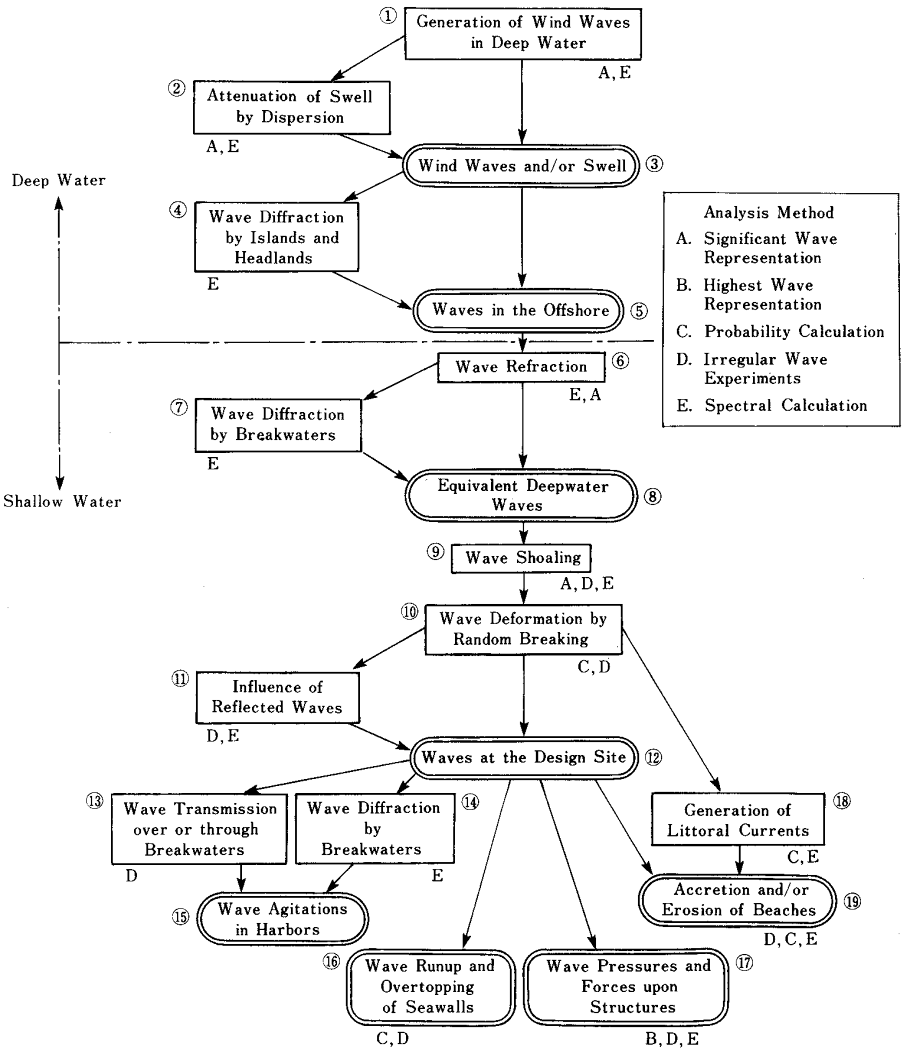

Fig. 1.1. Flow of the transformations and actions of sea waves with suggested methods for their calculation.[7]

toward the shore, after they have been generated and developed by the wind in the offshore region. The various types of wave transformations are schematically shown in Fig. 1.1.[7]

First, wind waves become swell when they move out of the generating area. The height of the swell gradually decreases with distance as it propagates (② in Fig. 1.1). When wind waves and swell encounter an island or a headland during their propagation in deep water, they diffract and penetrate the obstacle (④ in Fig. 1.1).

When waves enter an area of depth less than about one-half of their wavelength, they are influenced by the sea bottom's topography. These waves are called intermediate-depth water waves. Where the water is shallower than about one-twentieth of a wavelength, the waves are called long waves. For the sake of simplicity, both intermediate-depth water waves and long waves may be classified together and called shallow water waves; this terminology is employed in the present chapter. Waves in an area having a depth greater than about one-half of a wavelength are called deepwater waves (⑤ in Fig. 1.1). In a shallow bay or estuary, wind-generated waves may become shallow water waves during their process of development. In such a case, wave forecasting or hindcasting needs to take into account the effect of water depth on the wave development.

Having propagated into a shallow region, waves undergo refraction by which the direction of wave propagation, as well as the wave height, varies according to the sea bottom's topography (⑥ in Fig. 1.1). Concerning waves inside a harbor, the phenomenon of diffraction by breakwaters is the governing process (⑦ in Fig. 1.1). Although not shown in Fig. 1.1, wave attenuation due to bottom friction and other factors may not be neglected in an area of relatively shallow water which extends over a great distance with a very gentle inclination in the sea bottom. For convenience, the change in wave height due to wave refraction, diffraction and attenuation is often incorporated into the concept of *equivalent deepwater waves* (⑧ in Fig. 1.1). Equivalent deepwater waves are assigned the same wave period as deepwater waves, but the wave height is adjusted to account for the change due to wave refraction, diffraction and attenuation.

Waves propagating in a shallow region gradually change in height as a result of the change in the rate of energy flux due to the reduction in water depth, even if no refraction takes place. This is the phenomenon of wave shoaling (⑨ in Fig. 1.1). When waves reach an area of depth less than a few times the significant wave height, waves of greater height in a group begin to break one by one and the overall wave height decreases as the wave energy dissipates. This is wave deformation caused by breaking (⑩ in Fig. 1.1).

Waves arriving at the site of a proposed structure (⑫ in Fig. 1.1) will experience the above transformations and deformations of wave refraction, diffraction, shoaling, breaking, etc. If a long extension of vertical breakwater is already located in the adjacent water area, or if the design site is within a harbor, the influence of waves reflected from neighboring structures must be added to that of the waves arriving directly from offshore (⑪ in Fig. 1.1). These wave transformations and deformations will be discussed in detail in Chapter 3. Once the characteristics of the waves at the site have been estimated, design calculations can be made according to the nature of the problem. For example, the problem of harbor tranquility requires the analysis of waves transmitted over or through breakwaters (⑬ in Fig. 1.1), waves diffracted through harbor entrances (⑭ in Fig. 1.1) and waves reflected within a harbor. These will be discussed in Chapter 6.

The planning of seawalls and revetments to stand against storm waves requires the estimation of wave run-up and wave overtopping rate. Technical information for such problems is usually provided by conducting a scale model test in the laboratory or a set of design diagrams based on laboratory data. In such cases, the flow of calculation takes a jump from ⑧ to ⑯ in Fig. 1.1, because these data are prepared using the parameter of equivalent deepwater waves by directly incorporating the effects of transformations ⑨ and ⑩ into the data. Problems related to wave overtopping are discussed in Chapter 5.

In the design of breakwaters, the magnitude of the wave pressure is the focal point that requires an appropriate selection of calculation formulas. Chapter 4 discusses the formulas for wave pressure and their applications. It is remarked here that littoral drift, which is associated with beach erosion and accretion, is closely related to wave deformation by breaking and is induced by the resultant longshore current (⑱ in Fig. 1.1).

In the process of calculating the wave transformations and deformations described above, the significant wave height and period are used as indices of the magnitude of random sea waves. These parameters are converted to those of the highest waves or other descriptive waves whenever necessary, as in the case of a wave pressure calculation. Thus, at first sight, this procedure may look the same as the conventional design procedure, for which the significant wave is regarded as a train of regular waves. In the present treatise, however, the effects of wave irregularity are accounted for the estimation of the respective wave transformations, and the resultant height of the significant wave after such transformation often takes a value considerably different from that obtained with the regular wave approach.

1.2.2 *Methods of Dealing with Random Sea Waves*

At present, the following five methods are available to deal with the transformation and action of random sea waves:

A. significant wave representation method
B. highest wave representation method
C. probability calculation method
D. irregular wave test method
E. spectral calculation method

The significant wave representation method takes a train of regular waves with height and period equal to those of the significant wave as representative of random sea waves. Transformations of sea waves are estimated with the data of regular waves on the basis of theoretical calculation and laboratory experiments. The method has widely been employed in the field of coastal engineering since the introduction of the significant waves as the basis of the S-M-B method for wave forecasting. It has the merits of easy understanding and simple application, but it also has the demerit of containing a possibly large estimation error, depending on the type of wave phenomenon being analyzed. Diffraction, to be discussed in Sec. 3.2, is an example: the wave height behind a single breakwater may be estimated to be less than a third of the actual height if the diffraction diagram of regular waves is directly applied. The design of a steel structure for the sea is another example in which the maximum force exerted by individual waves is the governing factor. If the structure is designed against a regular wave equal to the significant wave, the structure will most probably fail under the attack of waves higher than the significant wave height when the design storm hits the site.

The danger of underestimating wave forces through the use of significant waves was well understood at the early stages of construction of offshore structures such as oil drilling rigs. It is an established practice to use a train of regular waves of height and period equal to those of the highest wave, and to design structures against this train of regular waves. This is called the highest wave representation method herein. The method is mainly used for structural designs.

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In contrast to the above examples, the phenomenon of diffraction is quite sensitive to the characteristics of the wave spectra, especially to the directional spreading of wave energy. In the analysis of diffraction, refraction and wave forces upon a large isolated structure such as oil storage tank in the sea, calculation is made for individual components of the directional spectrum. The resultant total effect is estimated by summing the contributions from all components. This is called the spectral calculation method.

The rate of wave overtopping of a seawall and the sliding of a concrete caisson of a vertical breakwater differ from the previous examples in the sense that the cumulative effect of the action of individual waves of random nature is important. The probability distribution of individual wave heights and periods is the governing factor in this type of problems. The phenomena of irregular wave run-up and wave deformation by random breaking belong to the same category. The calculation of these cumulative wave effects may be called the probability calculation method.

If a large wind-wave flume of a wave flume with a random wave generator is available, wave transformations and wave action on structures can be directly investigated by using simulated random water waves. This is the irregular wave test method. At the time of publication of the first edition of this book, the reproduction of directional random waves in model basins was possible only at a limited number of hydraulic laboratories in the world. Since then, many laboratories have been equipped with multidirectional random wave generators and become capable of carrying out model tests of various problems, including random wave refraction and diffraction. It may be said that the majority of hydraulic model tests related to sea waves are now carried out with random waves, and wave tests with regular waves are mostly reserved for fundamental research purposes.

In Fig. 1.1, the symbols A to E indicate the analysis method appropriate to the respective phenomenon. As can be seen, the problems related to random sea waves must be solved by selecting the appropriate calculation method among the five, A to E, to obtain a safe and rational design. None of the five methods can be used alone to treat all problems concerning sea waves. This stems from the complicated nature of waves in the real sea. In the following chapters, the above methods of analyzing the various wave phenomena are presented and discussed.

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