Chapter 9

THE SIMILITUDE OF SCALE MODELS FOR THE STUDY OF SEICHES IN HARBOURS

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PREAMBLE

The study of seiches in harbours is a relatively new scale model technique and poses many problems of similitude. We do not attempt here to be complete and consider all the questions that it poses, nor even to give a detailed account of the studies that the NEYRPIC LABORATORY is now carrying out on this subject. Our purpose is simply to set forth the conclusions that we consider have already been reached and the principal rules of similitude resulting from them. We hope thus to encourage as wide an exchange of opinion as possible.

I - BRIEF SUMMARY OF SOME GENERAL PRINCIPLES APPLYING TO SIMILITUDE

Contrary to a too widely held opinion the *"best"* scale is not the greatest possible scale. Basically model scales must be determined by considerations of economy.

It is clear for example that a model which costs 10 million francs and effects a saving of the order of 200 million francs is preferable to a larger and more accurate model which may effect perhaps a saving of 20 millions more, but which costs 50 millions instead of 10.

In practice the factors affecting the choice rarely present themselves so precisely. Normally, it is almost impossible to evaluate even roughly the overall economies which will result from the model study, let alone the way in which the economies will vary as a function of the accuracy of the tests. Thus, determining the optimum scale becomes more an art than a science, and the value of the results will depend above all on the knowledge possessed by the designer. Laws of similitude are the most important part of this knowledge, for not only do they allow the designer to estimate the degree of accuracy to be expected from a model but above all they allow to design the model soundly and to realise the optimum accuracy compatible with a prescribed research budget.

The first step in the study of similitude is not the discussion of detailed equations but essentially an overall survey of the problem and its physical nature. For example it is impossible to design a model well without first having an idea of the causes and origins of the phenomena studied. For this reason, we shall be led to establish a hypothesis on the origin of seiches, in order to be able to discuss the design of the models, but we do not intend discussing here the problem of the origin of seiches which is the object of a special chapter in the study from which this paper is drawn.

Such an overall survey of the problem allows the fundamentally wrong ways of approaching it to be avoided, it allows the line to be drawn between that which is reasonable and that which is not. Very often too it allows the main steps in the study to be determined, and eventually the necessary number and nature of the models.

The detailed study of the equations of the phenomena will follow and will lead to the more accurate evaluation of the approximations, scales, distorsions, etc.. and definitely settle the number of models necessary as well as the rules of similitude applicable to each of them. It is indeed well known that very often it is more economical to construct several models for the study of different phenomena than to try to study them all on one model. For example for a harbour the overall study can be made to a scale of 1/150 while particularly important structures (the harbour entrance for example) are studied to a scale of 1/75, and the stability of individual structures to 1/40.

We shall see that for seiche studies it may be necessary to construct a model to a scale of the order of 1/1000 and that if, for instance, it is required to study seiches of 40 seconds as well as seiches of 4 min. it may be necessary to have two different models even though the same phenomenon is to be studied, only one parameter having changed. Happily studies on the resonance frequencies of moored ships make it possible in most cases to reduce the range of periods to be considered and therefore to avoid such duplication of models.

Summing up, the problem of similitude is far from simple and does not lend itself to stereotyped solutions. The engineer has at his disposal a number of complex means and he must know how to make best use of them. The better he knows the tools at his disposal the more efficient and economical will be the solutions.

II - HYPOTHESIS ON THE ORIGIN OF SEICHES

As we have mentioned above it is not possible to conceive a model without admitting some working hypothesis on the origin of the phenomena to be studied. For example it is clear that a model built for the study of harbour seiches will be arranged in a completely different way, according to whether it is supposed that the seiche comes from the ocean in the form of progressive waves or that seiche is caused by local variations in atmospheric pressure, by wave amplitude fluctuation, etc..

For the purpose of limiting our discussion and of making it clearer, and *not* with the object of giving an opinion about the origin of seiches, we shall discuss models conceived according to the first hypothesis, that is to say, by assuming that seiche movements are provoked by progressive waves or *"seiche waves"* coming from the ocean.

This hypothesis has the following advantages for our purpose :

- it is plausible and fairly generally accepted ;
- it permits the discussion of most of the similitude problems which arise when other hypotheses are considered ;
- it allows a simple and instructive comparison to be made with problems relating to the study of storm waves ;
- it leads to models which are fairly easy to operate (in fact the majority of studies on seiche in scale models are, implicitly at least, based on this hypothesis).

With this hypothesis the seiche studies present themselves very much in the same way as storm wave studies. This analogy is useful, but dangerous if applied without caution ; for this reason the main part of the following is a list of the differences between seiche studies and wave studies.

III - ESSENTIAL DIFFERENCES BETWEEN STORM WAVES AND SEICHE WAVES

Both seiche waves and storm waves belong to the large family of gravity waves. The latter differ from the former only by the order of magnitude of certain parameters, in particular :

The period

The order of magnitude of the periods of seiche waves most dangerous to moored ships is two minutes or 120 seconds, while a period of 12 seconds is already fairly long for a storm wave.

The steepness or camber

Dangerous storm waves while still in the ocean have cambers of a few per cent and only exceptionally approach the theoretical limiting camber of 14 % . On the other hand seiche waves in the ocean have a much smaller camber. For example a wave of 2 minute period has a length of the order of 20 Km. in deep water (several thousand metres), while its amplitude might be of the order of 2 cm. only. The latter figure is reasonable, as such a wave would have an amplitude of about 20 cm. when it arrived in a depth of 10 metres (two dimensional propagation and no reflection being assumed). Consequently the camber of seiche waves in the ocean is of the order of 10^{-6} (one to a million) or 10,000 times smaller than that of the longest storm wave.

Before drawing from these facts the conclusions applicable to the technique of scale models, it is well to stop a moment to consider their significance. It is necessary that the mind which is used to the normal harbour problems should acquire a new outlook for seiche phenomena. It is necessary to become used to thinking of these phenomena in their proper scope and proportion.

The difference in the order of magnitude of the periods, of 1 to 10 for example, causes still more important differences in the dimensions of the area to be considered in the study. If the relation between the periods is 10 it can be deduced that the ratio between the wave lenths, at equal relative depths, is 100. This completely changes the scope of the phenomena : where, for storm waves, it was necessary to consider a radius of perhaps 10 kilometres around the harbour, for seiches, it should be necessary as a first approximation to consider a radius of 1000 kms. Where it was necessary to consider the influence of the sea bed down to a depth of 50 or 100 metres, it now becomes necessary to consider down to a depth of 5,000 or 10,000 metres. In other words studies will easily extend over a whole ocean, and, as we shall see later even this may not be sufficient.

For example let us consider a wave in infinite depth and of 2 minute period, it should have a length of about 22.5 km. Depths therefore will have a noticeable influence on the propagation when they are less than about 10,000 m. In other words such waves can never be said to be where the depth is *"practically infinite"*, therefore they are subject to refraction even in the open sea and are only exceptionally propagated in a straight line.

Supposing the origin of some seiche waves to be known (for example a zone of atmospheric disturbance) their propagation in the ocean can be studied only by means of refraction diagrams, analogous to *"wave plans"* but sometimes covering the whole ocean. By means of these diagrams *"lens"* effects which concentrate the seiche waves on certain points of the coast may be predicted and thus it may be explained why certain ports are particularly subject to this type of phenomenon.

It is known that waves have an extraordinarily long life and that their progress has been followed for several days over thousands of kilometres. It is also known from theoretical studies and from observations that the longer a wave the greater is the length of its life. The way in which length of life varies with wave length is not exactly known but if we suppose, for the sake of definiteness, that the distance travelled by a wave is proportional to its wave length in infinite depth, (which is probably close to the truth), seiche waves should be able to travel hundreds of thousands of kilometres, that is to say, to go round the world several times before dying.

The extraordinarily small camber of seiche waves also contributes to increase their longevity. Partly by reducing the relative effect of turbulence but mainly by allowing the reflection of seiche waves on coasts where the energy in an ordinary wave would be almost completely expended.

We touch there on an extremely important aspect of the behaviour of seiche waves.

Experimental studies have confirmed the fact, predicted by theory, that the smaller the wave camber the better the wave is reflected on a beach of given slope (see (1)). It is evident that tests cannot be carried out on waves having a deep water camber of 10^{-8}, but by using theoretical formulae it is possible to make reasonable extrapolations. In particular M. MICHE has shown that there was theoretically total reflection if :

$$\gamma < \sqrt{\frac{2\alpha}{\pi}} \frac{\sin^2 \alpha}{\pi}$$

or for gently sloping beaches

$$\gamma < 0{,}254\ \alpha^{5/2}$$

γ being the camber $\frac{2a}{L}$ and α the slope of the beach.

It can be deduced from this that waves with a camber of 10^{-8} are perfectly reflected from all beaches with a slope greater than 0.83 % . Most beaches would therefore reflect seiche waves as well as vertical walls would. By different reasoning M. IRIBARREN has arrived at similar conclusions.

Thus it is seen that seiche waves once created are particularly durable. They consume extremely little energy during their propagation and can be reflected without any noticeable loss of energy from coasts which are fatal to ordinary waves.

It is probable for example that the long straight beach of the *"Landes"* forms a magnificent mirror which reflects the seiche waves coming from the North Atlantic, towards the North coast of Spain. And it is known from the remarkable works of Professor IRIBARREN that numerous ports on this latter coast are subject to seiche phenomena. (fig. 1)

Broken coastlines are probably worse reflectors, nevertheless it is rather tempting to think that the French coast between BRITTANY and BIARRITZ plays a part in the amplification of seiches in the Cantabrian harbours by acting as a giant concave mirror.

There we leave this discussion which as can be seen is still capable of considerable development (see fig. 2 and 3). The long life of seiche waves and the ease with which they are reflected, make it theoretically desirable to consider them on a map of the world, to follow their journeys from ocean to ocean and their rebounds from continent to continent. But in reality the phenomena are so complex that it is safer to risk only fairly simple deductions, such as we have done for the Landes coast. We have touched on the overall problem only to put the discussion of the model studies in the necessary perspective and we might almost say the right atmosphere.

IV - ESSENTIAL DIFFERENCES BETWEEN SCALE MODEL STUDIES FOR SEICHES AND FOR ORDINARY WAVES

These differences are numerous and far reaching, without entering into too many details we give the most important below.

1°) Preliminary studies

When designing a scale model for studying the penetration of waves into a harbour, one of the first steps is to draw a wave pattern (refraction diagram) in order to know what position and what direction it is necessary to give to the wave generator. Sometimes the latter can be placed in such depths that the wave hardly begins to turn and consequently still presents a straight front.

This never happens for seiches because, as we have seen, the latter will always have turned to some extent. It will nevertheless be necessary to place the paddle in a position where although the crests are refracted they still remain almost straight. (Unless a *"snake-type"* wave maker is used, see (2)). For each separate problem it is necessary to make special appropriate refraction diagrams, but it is however possible to make a few very general remarks.

We know that seiche waves are refracted even over the greatest depths of the ocean ; *the refraction diagram must therefore begin in mid-ocean* in fact it must cover the whole area between the supposed point of origin and the point of arrival. Diagrams on such a scale pose problems which have not previously been considered because to be absolutely accurate it is necessary to take into account the earth's curvature and the acceleration of Coriolis. However theoretical studies seem to show that the latter has a practically negligible influence.

The laws of refraction lead then to the following general results :

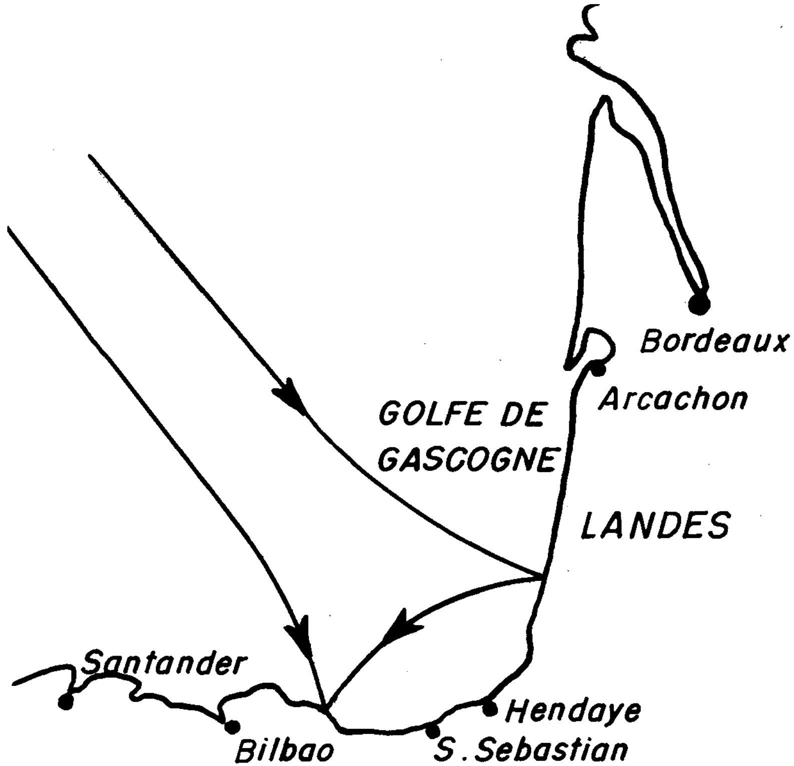

Fig. 1. A point on the north coast of Spain can be reached by a seiche wave either directly or after reflection on the French coast of the "Landes". The direct and reflected waves may combine and reinforce each other.

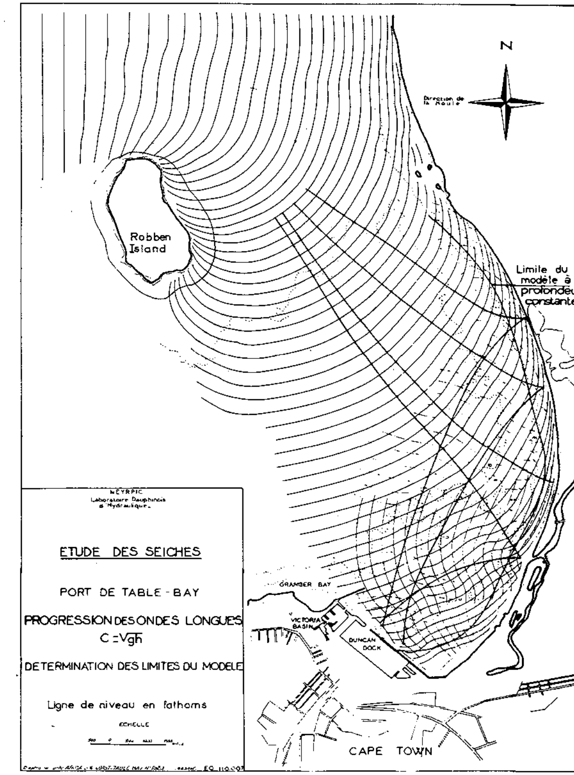

Fig. 2. Table-Bay harbor is a good example of the possible "concave mirror" effect of a large bay. The concentration of energy due to the shape of the adjoining coast is still enhanced by the presence of the jetty at the north of Victoria basin.

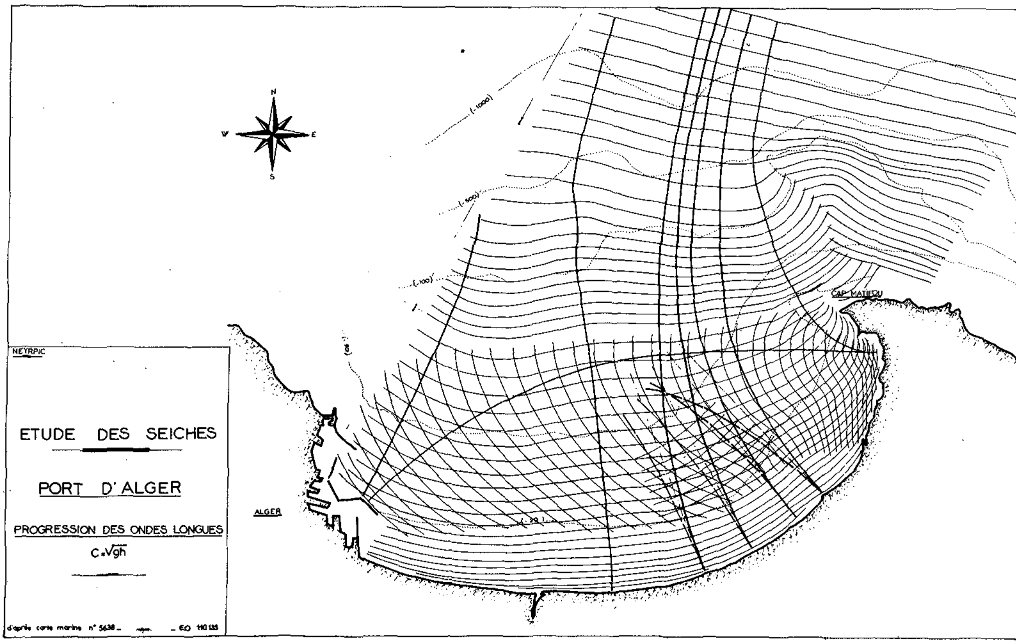

Fig. 3. Algiers, although placed at the end of a bay, like Table-Bay Harbor, is only slightly subject to "concave mirror" effect. By comparing Fig. 2 and 3, the great importance of the presence of Robben Island can be appreciated.

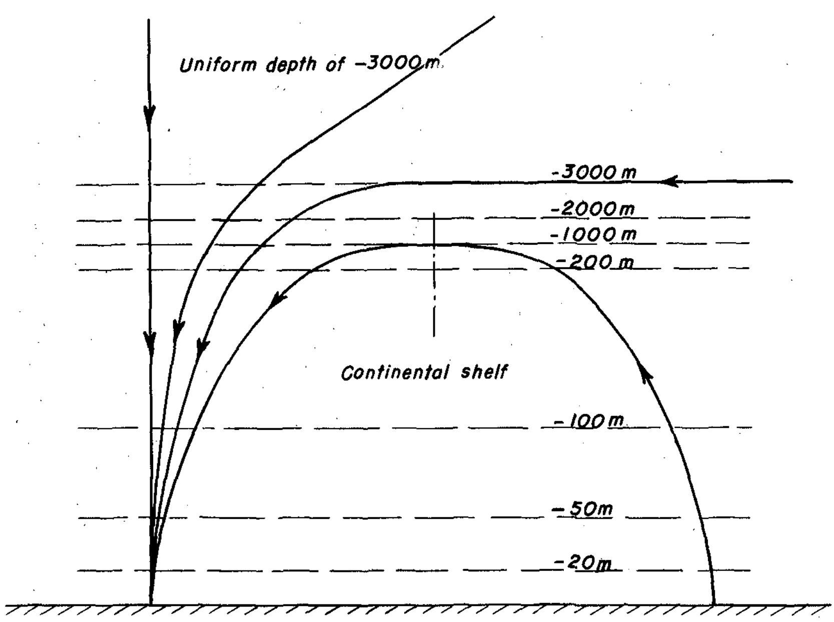

Fig. 4.

When the shape of the sea bed is not too involved, in particular when the bed contours are roughly parallel to the coast, then, in depths suitable for establishing a harbour, the crests are always practically parallel to the coast-line. In the ideal case when the bed contours are exactly parallel to the coast (fig. 4) it can be calculated that a wave of 2 minute period which has originated in deep water (4,000 m. for example) cannot have an angle of incidence greater than about :

20°	for 200 m.	depth
11°	for 100 m.	depth
5°	for 20 m.	depth
3°30'	for 10 m.	depth

If the hypothesis is accepted that seiche waves come from the ocean it can be seen that it will in general be sufficient to have a wave generator of fixed direction.

With this hypothesis, which we have adopted here, let us repeat, only to limit the discussion, *it is not therefore permissible to study seiche excitating waves having any incident angle whatever in relatively shallow water.*

2°) Influence of the continental shelf

Emergent lands are not the only reflectors of seiche waves and the refraction diagrams for these waves may therefore be very delicate. Without wishing to treat this delicate question completely it is however particularly interesting to consider it in view of the possible influence of the continental shelf.

Let us consider first the inverse of the usual refraction diagram, that is to say a diagram representing the propagation of the seiche wave from a given point of the coast (fig. 5).

Let us suppose, for example, that a bay is in a state of resonance and that its entrance emits waves which are almost circular, in a depth of say 20 m. It is seen that only the energy emitted within an angle of 10° (or about 5 % of the energy if the emission is not directional) has a chance of escaping into the ocean. The remainder is directed towards the coast by a phenomenon of total reflection which is produced principally on the outer limit of the continental shelf. It is seen therefore that this limit and the coast can send seiche waves back to each other many times, and thus create appreciable resonance phenomena. Moreover the mechanism of refraction is not the only factor liable to produce similar phenomena.

When the edge of the continental shelf is a long way from the coast it will not be possible to represent it on a model of reasonable scale but on the other hand the resonance phenomena will be less marked. On the contrary when the continental shelf is relatively narrow it may play an important part in the selection of the dangerous frequencies and it will be imperative to study its influence with care. For coastlines and continental shelves of very complicated shapes it may even be necessary to make a special preliminary model representing to a very small scale a wide expanse of coast including the continental shelf and a sufficient extent of the neighbouring abyssal depths.

This latter type of model also poses similitude problems of its own, choice of scales, etc..., that we shall not consider here.

3°) Extent of the area to be represented on the main model - Scale in plan

We have seen how seiche waves are very easily reflected.

Wide bays, whether bordered by beaches or not, can thus form resonance basins for incident seiche waves and as we have seen above (example of the coast of Landes) extensive coastlines can form reflectors which cause the seiche waves to converge on certain particular points.

Here again diagrams and, more generally, studies on the map, usually allow to limit to a minimum the extent of the areas which must be reproduced on the model. However these areas will in general be more important than those that it is necessary to consider for wave models. For example when a harbour is situated in a bay, it may be necessary to represent the whole of the latter even if it extends over many kilometres, or even tens of kilometres.

Besides, the necessity of reproducing the shape of the bed as far as the zone where the wave crests are sufficiently straight, will lead to increasing the extent of the model beyond any local features which may provoke important refractions or diffractions - shallow depths, head lands, etc..

It is important to insist here on the fact that the study of a port cannot in general be separated from that of the oceanic *"medium"* in which it is situated. It would evidently be extremely economical to be able to limit oneself to the study of the *"interior problem"*, the model being confined then to the representation of the harbour, and the excitation being provided at the entrance or in its immediate neighbourhood by means of suitable apparatus.

This type of approach allows the modes of resonance of the harbour to be disclosed, but in general it does not allow their amplitudes to be determined. In effect the latter depend directly on the amplitude of the agitation at the harbour entrance and this agitation has a local value which depends essentially on the pattern of the outside movement.

In a large harbour it will be possible to suppress all the forms of oscillation indicated by this type of test only by barring the water area in all directions, which would create (at great cost) inadmissible obstacles for navigation. On the other hand if limited structures with

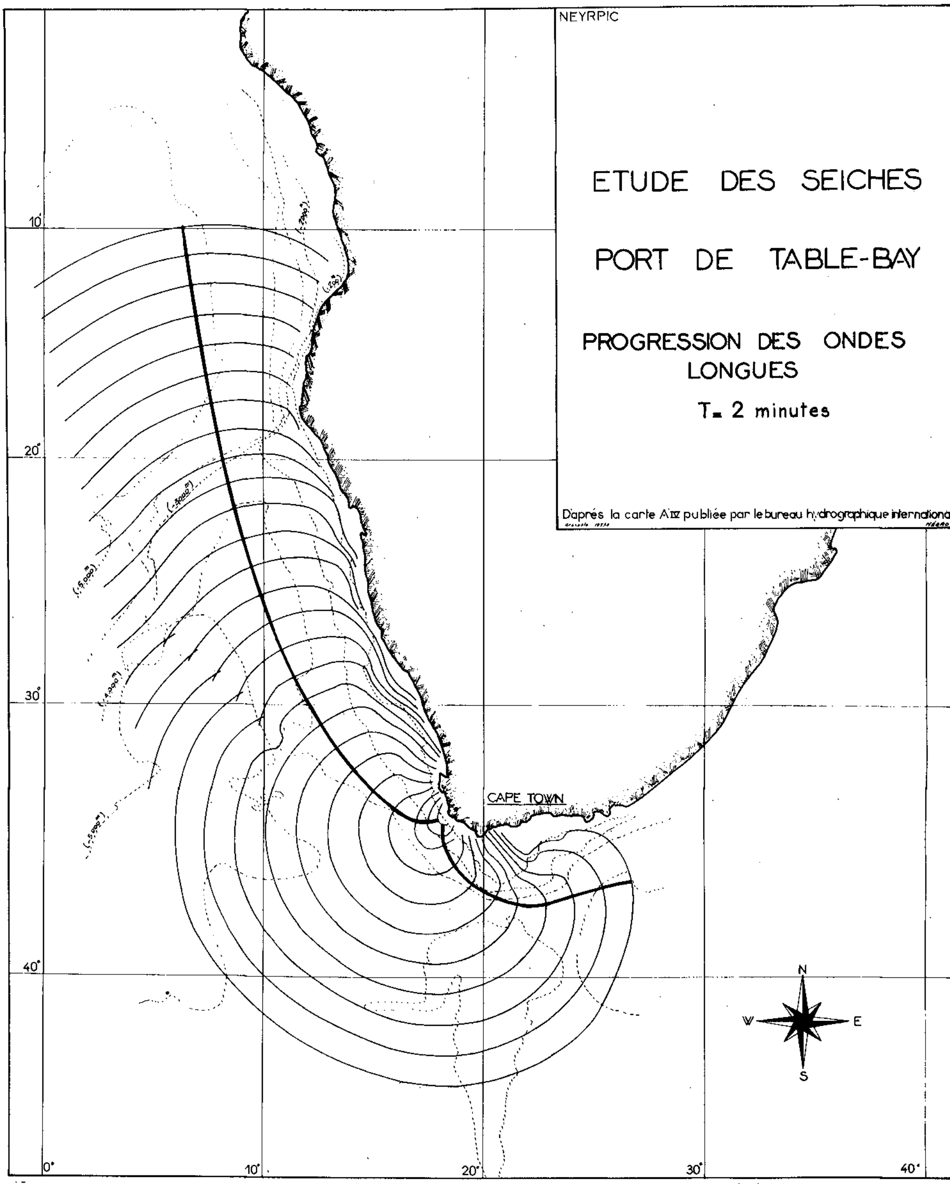

Fig. 5. An "inverse" refraction diagram is often the best way to have a bird's eye view of the maximum possible incidence with which seiche waves coming from deep water can reach the coast; or, vice versa, visualize how the energy of a coastal source of seiche waves will radiate.

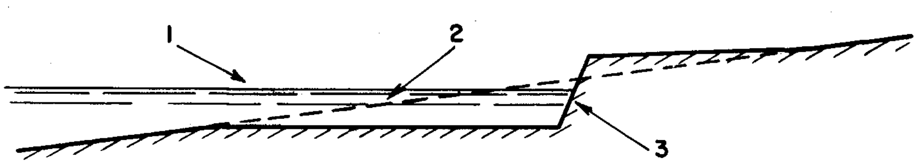

Fig. 6.

the aim of suppressing only a few modes of oscillation are built, there is a risk of allowing and even of favouring the formation of other modes already amplified by outside interference.

At this stage it is interesting to mention that it is sometimes possible to study separately, the resonance of the outer and of the inner water surfaces. This is the case when the port entrance is so narrow that it can be assumed that, on the one hand, the interior state of resonance does not noticeably affect the outside agitation, and on the other hand the interior agitation depends for practical purposes only on the local value of the exterior vertical amplitude at the centre of the entrance.

The exterior problem may then be studied without the handicap of having to ensure a suitable similitude for the narrow basins and for the shallow depths of the harbour, this allows a smaller scale to be used. On this model, the *"amplification coefficient"* relating to the exterior of the port is determined ; this coefficient is the quotient of the amplitude at the harbour entrance divided by the incident amplitude.

The interior problem may then be studied, and new *"amplification coefficients"* are defined as being the quotients of, the amplitudes measured at different points divided by the amplitude at the entrance.

This second study can be made to a relatively large scale without necessitating a very large and costly model. It allows precise measurements to be made, as well as convenient and detailed studies of the modifications to be effected to the interior installations.

Hence for each frequency and for each measuring point the overall coefficient of amplification is obtained from the product of the interior and exterior coefficients.

Summing up, we see that the model study can therefore only be limited to the interior problem in exceptional cases. This will be permissible either for ports receiving only vessels of small tonnage when it may be possible without serious inconvenience to divide the water area into small basins, or when the outside topography is so simple that it is possible to predetermine graphically the characteristics of the outside agitation, or again when the exterior *"coefficients of amplification"* have been determined on a preliminary model.

Therefore, in the general case, the extent of the area to be represented on the model is much greater than in ordinary wave studies. Fortunately the great length of seiche waves justifies the use of very small horizontal scales. Further it is possible to use the artifice of distortion and thus avoid working with layers of water which are too thin.

4°) Distortion of the bed

In view of the extent of the areas to be represented it is very important to be able to use horizontal scales of the order of 1/1000 or 1/2000 for example.

If the same vertical scale were employed, the depths of 10 m. which are usual in important harbours would be represented on the model by water thicknesses of 0.5 to 1 cm., for which the effect of friction would be too great. It is known that the latter effects can be reduced by means of scale distortion ; as their importance is negligible in nature, the greater the distortion the better, from this point of view, it is therefore essential to examine whether distortion is permissible and to what degree it is compatible with similitude.

As is known it is generally not allowable to distort a model designed for the study of penetration of waves into a harbour. The main objection is that the similitude of refraction is not retained. Besides, the similitude of the *"reflecting coefficients"* is also altered.

We shall have occasion to return to the latter point in the following. Concerning the former point it is important to mention that the similitude of refraction can be maintained, when the wave length to depth ratio (or relative wave length) is sufficiently large throughout the area reproduced, for the celerity to be given with satisfactory accuracy by the formula $c = \sqrt{gh}$ (1) . The useful range of distortion may be increased by the application of the functional distortion conceived by M. CARLOTTI, (3) but first we shall assume the use of ordinary distortion. The formula $c = \sqrt{gh}$ is valid to approx 5 % if

$$h_{cm} < 6\ T_s^2$$

In the sea for waves of 2 min. period the formula $\sqrt{gh}$ will therefore be valid (to app. 5 %) down to depths of

$$6 \times 14,400 = 86,400 \text{ cm. or } 864 \text{ metres}$$

On a distorted model with horizontal scale λ and vertical scale μ (time scale $\frac{\lambda}{\sqrt{\mu}}$) the same relation referred to prototype quantities (h and T) gives :

$$h < 6\ \left(\frac{\lambda}{\mu}\right)^2 T^2 \quad \text{or} \quad h < 6\ (\delta)^2\ T^2$$

δ being the distortion.

(1) We assume in the following that only fairly marked distortions are considered, for example distortions greater than 1.5 , for the sake of being definite.

The maximum prototype depth which can be represented by the distorted model is therefore inversely proportional to the square of the distortion. For a distortion of 2 it would be in the preceding case 216 m. which will very often be sufficient. For a distortion of 10 it would be no greater than 8.64 m. which would certainly be insufficient.

The above formula permits an instructive general discussion. We shall make the simplifying assumption that the extent of the bed to be represented is determined by such considerations as topography, etc... so that the greatest depth h is known. We shall also assume that the vertical scale μ is fixed in order to ensure that depths of the order of 10 m. will be represented by an adequate thickness on the model. Then we can write

$$T^2 \lambda^2 > \frac{h \mu^2}{6}$$

It can be seen that the greater the period of the seiche the smaller the horizontal scale can be. On the other hand the greater the period the greater is the wave length and we have already seen that the extent of the area to be represented increases in proportion with the latter. (We shall see later that this is also the case for the zones of the model necessary for damping the waves which are reflected to the sea). There is thus a sort of compensation, the scale admitting of some reduction when the area to be represented must increase.

Consequently the design of a model depends directly on the period of the seiche that is to be studied. If it is necessary to study a wide range of periods it may thus be economical to construct several models, in order to avoid the necessity of reproducing the large areas required for the longer periods, to the large scale required for the shorter ones.

A few numerical examples will help to clarify the above.

Let us suppose that it is desired to study seiches of relatively short period, e.g. 1 min., and that it is necessary in this case to represent an area which extends over depths of up to say 100 m.

The maximum allowable distortion is then of the order of 1.5. If the vertical scale chosen is 1/400 the horizontal scale will be 1/600.

For seiches of 2 min. it may, for instance, be necessary to go up to a maximum depth of 150 m. The distortion may then be 3 which gives with the same vertical scale as above a scale in plan of 1/1,200.

If it is desired to study seiches of 4 min. the maximum depth being 200 m., a distortion of 4 may be used. Therefore with the same vertical scale as above the scale in plan would be 1/1600. This much smaller scale may allow the model to be fitted into the same space as the first although the region represented is more extensive and the accessory organs of the model are relatively more bulky (see later paragraph 6).

If there is reason to think beforehand that the most dangerous periods are contained within a relatively narrow range (for example as obtained from the value of the resonance period of moored vessels), it is possible to limit the studies to a model designed for a carefully chosen mean period. This model will also be able to serve for the approximate study of resonances of widely different periods; although in this case it will only give indications of the possible existence of other dangerous frequency ranges, which if they are sufficiently disturbing may justify the modification of the model.

The use of functional distortion allows, everything else being equal, the horizontal scale of the model to be reduced by making greater distortions permissible. But it also has the inconvenience of being essentially adapted to a fairly narrow range of periods and moreover to a narrow tidal range.

5°) Similitude of reflections - distortion of amplitude of seiche waves

Although very different, these two questions are directly related. It is known indeed that the coefficient of reflection of a structure, of a beach etc.. is essentially a function of :

- the slope of the structure
- the camber of the wave
- the scale.

Distortion of depth increases the slopes and consequently the reflections. Augmenting the camber of the waves reduces the reflection. Reducing the scale increases the reflection.

The latter effect is relatively unimportant, it is the only one which plays a part in ordinary wave models, where the distortion of depths is usually forbidden and where the distortion (increase or decrease) of the amplitudes can generally be avoided (on the inconvenience of this distortion from the point of view of the similitude of reflections see (1).

On the contrary, seiche models will in general have both distorted depths and cambers, in view of the extreme smallness of the latter in nature. As the effects of these two distortions are opposed it can be hoped to correct one by the other. Let us examine this idea.

We have seen above that the limiting deep water camber of waves capable of being wholly reflected on a slope was given by

$$\gamma \neq 0{,}254\ \alpha^{n/2}$$

α being small.

For $\gamma = 10^{-6}$ we had $\alpha = 0.0083$. If the second example given above is considered (vertical scale 1/400 - horizontal scale 1/1200) it is seen that the distortion of the cambers (in infinite depth) would be $(3)^{5/2} = 15.6$. But on a distorted model the increase of camber from deep to shallow water is less than in the prototype. (The cambers in small relative depths are diminished in the proportion $(\delta)^{\frac{3}{2}}$, if the deep water cambers are the same). Consequently the distortion of the cambers in the important zone would have to be no greater than 3. The vertical scale of amplitudes would therefore be 3/1200 or 1/400. An amplitude of 20 cm. (in shallow water) would be represented on a model by 0.5 mm.

The preceding calculation tends to show that the effects of depth distortion can easily be more than compensated by a distortion of the amplitude and that in fact the necessary distortion is not very great and will often be insufficient to ensure a suitable accuracy of measurement.

Although some degree of over-compensation is justifiable in order to correct also the scale effect, there is nevertheless a risk of being led to the use of amplitudes which are too small. Therefore it may be interesting to further increase the distortion and thus to work with more reasonable amplitudes by means of devices allowing the correct coefficients of reflection to be restored.

For example a beach may be represented in the fashion indicated in figure 6. This artifice also introduces a source of error for it is not possible to choose the proportions in such a way that the phase of the reflections are reproduced as faithfully for normal waves as for oblique waves. It is necessary therefore not to use it unnecessarily ; in other words it is important not to exaggerate the amplitudes more than necessary (1).

In this respect it is also interesting to recall that the damping rate of water waves increases when their camber increases beyond a given value. This is due to turbulence phenomena. Figure 7 shows to what extent resonance coefficients can vary when the camber of the incident wave changes. This effect necessitates to assign a superior limit to the camber distortion in order to avoid unwanted extra damping. However this limit is usually superior to that resulting from reflection similitude requirements.

6°) Boundary conditions - absorbers, filters

It is known that the walls of test basins which limit wave models on the ocean side must be prevented from causing parasitic reflections which have no equivalent in the prototype. Therefore wave absorbers are placed along all walls which have no counterpart in nature. In the same way it is necessary to place an absorbing filter

(1) Incidentally it is worth noting that as the cambers are less than in ordinary wave models it will generally be possible to study the agitation by the *"starred sky"* method of M. BARILLON.

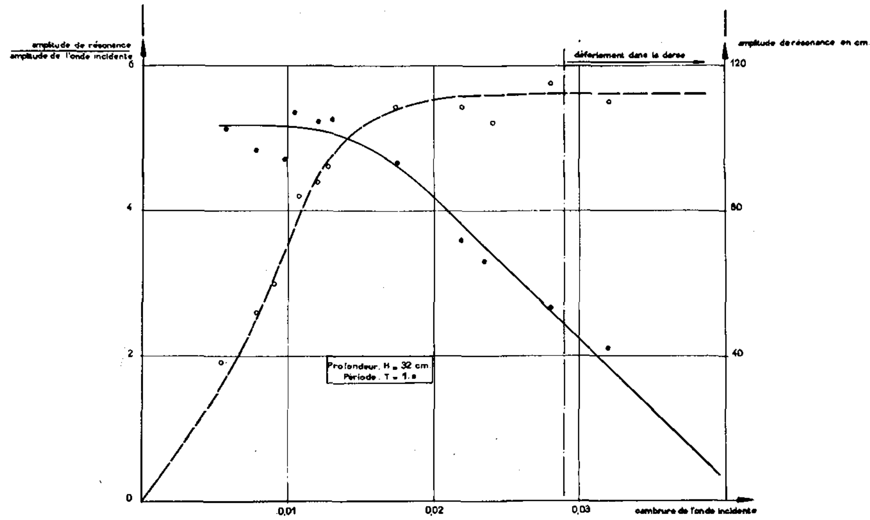

Fig. 7 - These curves have been plotted by M. LE MÉHAUTÉ in the course of his experiments on the resonance of rectangular basins.

The full line shows how the amplification coefficient decreases (from a maximum of about 5) when the *incident* wave camber (2a/L) increases. In the particular case to which this figure refers, the drop in amplification is sensible as soon as the incident camber is greater than about 1 % . Actual breaking in the basin (deferlement dans la darse) occurs for much greater incident amplitudes i.e. about 3 % .

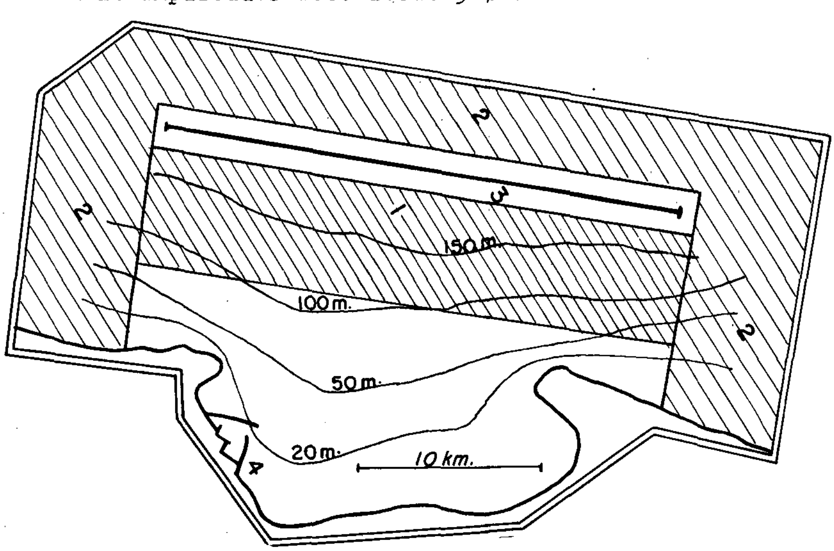

Fig. 8 - Typical aspect of a seiche model designed to reproduce boundary condition as well as possible. The width of the wave filters (1) and absorbers (2) is about one (local) wave length of a 2 mn seiche. It has been assumed that conditions were such that only one direction of wave machine (3) had to be used. Otherwise the space occupied by the filters-absorbers-wave-machine compound would be still greater than as shown above. Notice minuteness of the harbour (4) as compared to over-all extent of model.

in front of the wave paddle in order to minimize the parasitic reflections which can be produced on the latter.

As a first approximation it can be assumed that the minimum width of absorbing beaches or of filters is proportional to the wave length (local value in the model). A reasonable order of size being one wave length. The result is that the filters and dampers which take up little room in ordinary wave models become enormous on seiche models because of the great wave lengths involved. It will often happen that these devices will occupy by far the greatest part of the test basin, and the most striking characteristic of a well designed seiche model is the almost ridiculous minuteness of the harbour in relation to the total area of the model.

We have seen above that the distortion of the camber of seiche waves must not be exaggerated too much, consequently even on the model waves may be not only long but equally of slight camber. Wave dampers taking the form of beaches would have to have very gentle slopes and consequently to be extremely long and cumbersome to be efficient (see (1)) It is therefore wise to call on the ingenuity of specialists to obtain efficient dampers of as short a length as possible. When straight forward wave *"breaking"* is insufficient other damping means may be called upon : permeability, friction, resonance, overflowing, etc.. Except perhaps with the last of these, which is at present being studied in the laboratory, it seems necessary to have at least one wave length to spare in order to realise a sufficiently efficient damping.

An analogous problem poses itself for filters, which must be much more efficient on a seiche model than on an ordinary wave model, because of the much higher coefficients of reflection for seiche waves. Happily the slight camber required allows the use of very powerful filters. Here again it is necessary for such filters to act over approximately one wave length because they would create greater reflections than those they were intended to suppress if their action were too sudden. Refinements such as the progressive filter studied by M. LE MEHAUTE can effect an economy of space without altering the quality of the result.

Figure 8 is a schematic plan of a model corresponding to the characteristics studied above.

It can be seen how large a space is occupied by the wave dampers, filters, and paddles which are indispensable to the accurate realisation of the boundary conditions.

7°) Adjustment of the incident wave characteristics

Direction -

Because of the great width of the filters the wave paddle will sometimes be located in greater depths of water than it is normally convenient to represent to the vertical scale of the model.

As for ordinary wave models the representation of the sea bed is therefore usually stopped beyond a certain level at which the horizontal slab supporting the wave paddle is situated. On seiche models it is important to remember that this modification of the bottom falsifies the refraction, and consequently it is necessary to give to the paddle not the direction of the crests corresponding to its geographical position, but a direction deduced from an *inverse diagram*, starting from the wave pattern to be realised above the bottom actually represented.

Amplitude -

It is known how much the presence of waves reflected by the paddle (after having been reflected by the model) can hamper the exact measurement of incident amplitude in three dimensional wave models. The filters employed in this type of model are not very powerful because they must allow a wave of considerable camber to pass. They are therefore incapable of rendering the influence of multiple reflections utterly negligible.

The same difficulty is found for seiche models with the difference, however, that the power of the filters is limited in practice only by the available space. Although the energy reflected by the model represents an important fraction of the incident energy it is theoretically possible to considerably reduce the disturbances on the wave paddle. Summing up, if very powerful filters are used, it is possible to calibrate the wave generator plus filter unit while it sends waves into a perfectly damping beach and to use this calibration during the course of the tests, (although this procedure is usually not admissible without special precaution in ordinary wave models).

Frequency -

While amplitude problems are relatively easy to solve this is no longer the case for the frequency.

It is known that the phenomena of diffraction, refraction, wave breaking, etc.. vary smoothly with the frequency, while resonance phenomena behave in an entirely different manner. For example let us recall the work of Professor Mc NOWN (4) on the oscillations of the water in a circular harbour, where he has shown that in certain circumstances variations of frequency of the order of 1/1000 were able to change completely the character of the agitation, loops replacing nodes etc.. (see fig. 9).

This sensitivity of the agitation to small frequency variations is most marked when the boundaries of the body of water are good reflectors and when the wave length is small in relation to the dimensions of the area which is liable to resonate.

We know that for seiches almost all the natural limits of the water area are perfect reflectors and that on the other hand the regions to be represented are sometimes very extensive. A port opening into a fairly well closed bay will therefore be submitted to a seiche agitation which may vary completely for slight frequency variations. The interior of the port itself may react in very different ways to slightly different frequencies providing that its dimensions are great enough in relation to the local value of the wave length (linear dimensions of a few wave lengths being sufficient).

It is to be noted that if the port is situated in a very open bay (or a fortiori on a straight coastline) the ocean limit of the bay will be non reflecting and consequently the instability phenomena that we have just considered will be lessened. On the contrary, if the basins for the study of seiche were not supplied with spending beaches and filters there would be permanently quasi-stationary oscillating patterns which would transform one into another on the slighest provocation. Not only would the tests be uselessly complicated but above all they would lose all physical significance.

The results of tests can therefore be very different for neighbouring frequencies. We thus arrive at the following conclusions :

a) For tests at a fixed frequency, the value of the frequency must be kept extremely constant. It is not possible to generalize the degree of accuracy which must be obtained, for it depends in each case on the geometry of the water surface and on the frequency itself. It may even happen that movements of a given frequency cannot be established whatever the precautions taken to regulate the latter. (Two resonance periods are extremely close to each other but correspond to very different agitations). If the frequency is regulated carefully (for example to 1/1000) these accidents will not happen too often and will hardly affect the validity of the results. It is to be noted that a comparable constancy of depths must also be attained, and that all parasite movements of the water surface must be avoided (effect of wind for example).

b) If a discrete series of frequency values is used the most dangerous frequencies might be missed, or again only these values might be found, and either case can lead to a wrong interpretation. This suggests making tests with an incident wave whose frequency varies continuously with time.

If it is supposed that the frequency must be defined with a precision of the order of 1/1000 in order that the resonances can be reproduced without ambiguity, and that the establishment time for the fully developed resonance is about one minute (this can be verified on the model), the variation of frequency will have to be about 1/1000 per min. For example to try the periods between 1 min. and 3 min. about 17 hours of measurement are necessary. It is clear that this variation of frequency does not dispense with the need for precision, for the programme must be followed with great continuity if some resonances are not to be missed by too sudden drops (or rises) past a given frequency.

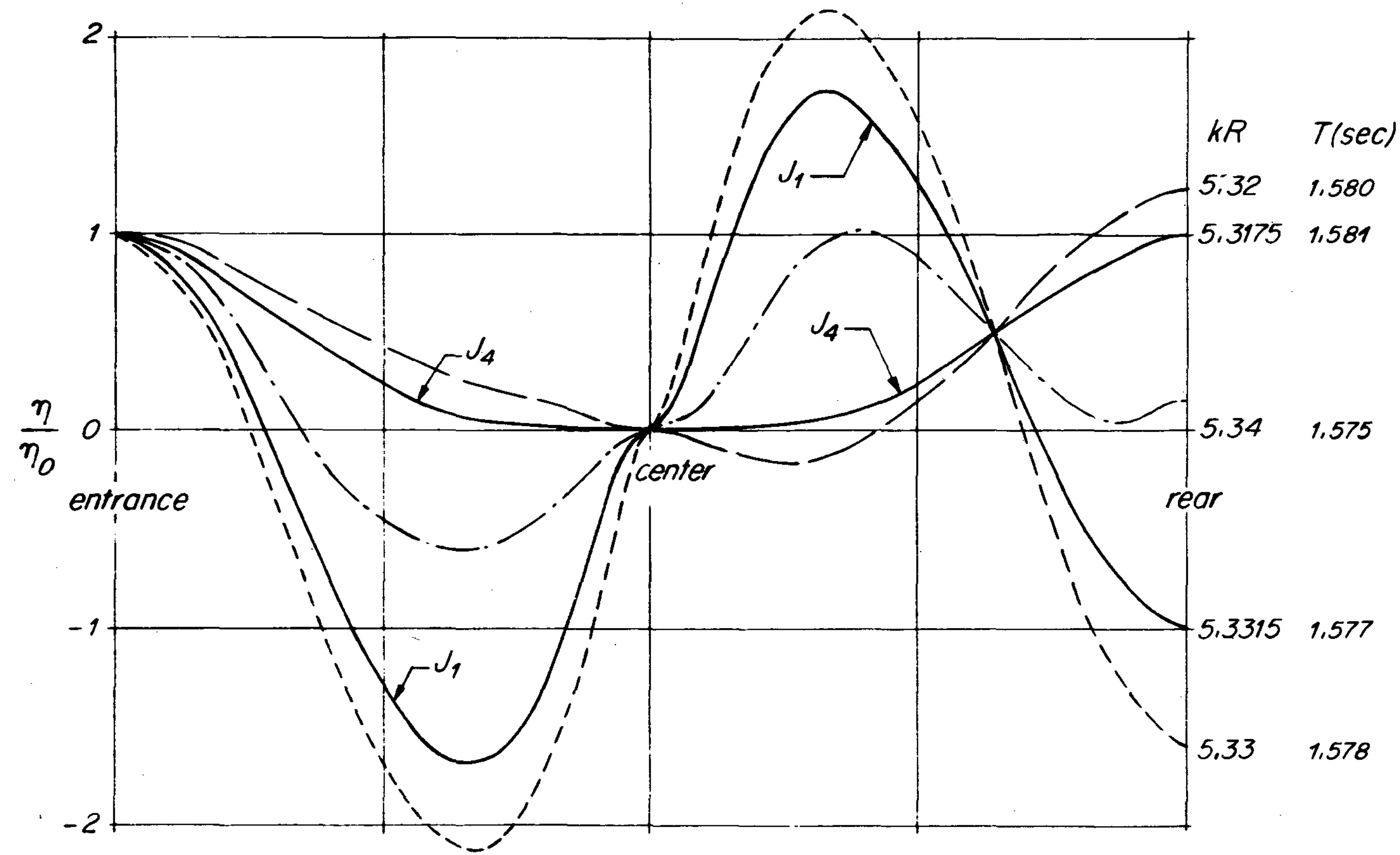

Fig. 9 – This figure is extracted from Professor Mc NOWN thesis on the oscillations of water in harbours (University of GRENOBLE), it shows the theoretical amplitudes of the oscillations in a circular harbour along the diameter passing through the center of the entrance. It can be seen that if the period passes from 1.578 seconds to 1.580 seconds the oscillation pattern changes completely.

Thus the exploitation of a seiche model can be visualized as a series of recordings made at fixed points, while the frequency glides imperceptibly from one value to another. The operation may have to be repeated for numerous tide levels and for each layout considered.

The application of the results thus obtained necessitates a knowledge, or at least sufficiently accurate hypotheses, of the nature of actual seiche waves. (Probability of frequencies and of spectrum widths). It is to be noted besides that starting from such knowledge or hypotheses, it is possible to make direct studies on the model of the seiches produced by irregular waves, such as can be expected in nature. In the absence of accurate statistical information this procedure does not seem to us advisable.

CONCLUSIONS

Seiche problems in harbours must be studied with the broad outlook necessitated by the magnitude of seiche wave lengths.

It is also essential to realise that the extremely slight camber of seiche waves causes their behaviour to differ widely from that of ordinary waves. Finally from all these considerations it follows that :

The preliminary studies must be made on an ocean wide scale, normally by means of refraction diagrams, as models cannot conveniently take into account the earth's curvature.

The continental shelf and analogous large scale formations should sometimes be made the object of special studies. In some cases a preliminary model representing a large area to a very small scale may be necessary.

The area represented by the model proper generally has to be much more extensive than that required for an ordinary wave study. The horizontal scale is therefore very small.

Distortion of the vertical scale becomes very useful in view of the smallness of the horizontal scale. It is fortunately allowable here in view of characteristics of seiche waves.

Exaggeration of amplitudes far from systematically falsifying the similitude of reflections, as on wave models, tends on the contrary to compensate for the effect of distortion in the vertical scale. However, one must be careful not to exaggerate the wave steepness.

Realisation of boundary conditions to a suitable degree of accuracy poses one of the most important problems in the study of seiche and leads to the use of very large damping devices and filters.

Adjusting the characteristics of the wave generating apparatus poses particularly delicate problems concerning the constancy of the frequency, which it should be possible to realise with great accuracy. Tests with a slowly varying frequency seem to be necessary for seiche problems because conditions of resonance sometimes vary rapidly in relation to the frequency.

In terminating these observations it seems important to insist again on the fact that we have limited the present discussion to models conceived in view of a particular hypothesis on the origin of seiches. If other hypotheses are considered the conception of the models will have to be modified, however the majority of the conclusions reached above will remain valid.

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RESUME

APERÇUS sur la SIMILITUDE des MODELES REDUITS DESTINES à l'ETUDE des SEICHES PORTUAIRES

Francis Biesel

Les grandes lignes de la conception des modèles d'étude de seiches portuaires sont étudiées dans l'hypothèse où les mouvements de seiches seraient causés par des ondes de gravité venant du large.

Les principales différences entre de tels modèles et ceux destinés à l'étude des houles sont exposées et discutées systématiquement.

De ces considérations, il se dégage principalement que :

Les études préliminaires doivent se faire à l'échelle océanique, en principe au moyen d'épures de réfraction, les modèles ne pouvant tenir compte convenablement de la courbure terrestre.

Le plateau continental et des structuro à grande échelle analogues doivent parfois faire l'objet d'études spéciales. Dans certains cas, un modèle préliminaire représentant une grande étendue à très petite échelle pourra être nécessaire.

L'étendue représentée par le modèlo proprement dit doit être, en général, beaucoup plus vaste que pour une étude de houle. Ainsi, l'échelle horizontale est-elle faible.

La distorsion des formes devient précieuse du fait de la petitesse de l'échelle horizontale. Elle est heureusoment autorisée, dans une certaine mesure, par les caractéristiques dos ondes de seiches.

L'exagération des amplitudes, loin de fausser systématiquement la similitude des réflexions comme sur les modèles à houle, tend au contraire à corriger l'effet de la distorsion de l'échelle verticale. Cependant, il faut se garder d'exagérer les cambrures.

La réalisation de conditions aux limites convenables pose un des problèmes les plus importants do l'étude des seiches et conduit à donner aux amortisseurs et aux filtres un développement considérable.

Le réglage dos caractéristiques do l'appareil génératour d'ondes poso des problèmes particulièremont délicats en ce qui concerne la constance de la fréquence qui doit pouvoir être réalisée aveó une grande précision. L'étude en fréquence lentement variable semblo s'imposer pour les problèmes de soichos, étant donné que les conditions de résonance varient parfois rapidemont on fonction de la fréquence.