

## The flow induced oscillations of marine structures

R. N. SAINSBURY & D. KING

### Mr Sainsbury

There are one or two points of correction and slight elaboration which I would like to make to the text of the Paper. I have been asked questions about equations (7)–(12). These are dimensionally stable provided  $M$  is recognized as a unit of mass and that  $E$  is recognized as a unit of force. There is, however, a dimensional error in Table 1. The lines for  $M^3$  and  $2/\rho D^2$  have unfortunately been left in units of weight. The later non-dimensional lines are, of course, correct, because the missing  $g$  has been cancelled out on the top and bottom lines, so the lines in which you have probably been most interested are still absolutely correct.

107. The values of  $K_s$ , towards the bottom, have been achieved by using an assumed value for  $\delta_s$  of 0.07, which was taken at the time to be as good a guess as could be made of a value typical of the sort of structures which we were considering.

### Mr King

I would like to comment on Fig. 16. While the fundamental pile frequency can be fairly readily calculated the sway loads are more ephemeral. The fundamental sway frequencies are included in the diagram to build up a complete picture. All figures on the outer two lines have been calculated from actual results, but the others, referring to sway, are guesstimates, as is the uncoupled sway frequency in Fig. 15.

109. In § 85 reference is made to the comparison between the direct determination of the eigenvalues by the QL method and the results of the more elaborate Sturm sequence analysis; Table 2 gives actual figures. The comparison of cols 1 and 2 appeared satisfactory, but at the time we were working fast and did not do a direct comparison of identical cases. The fit is not as good as it might be, particularly on the second mode. The pile mode was not located exactly by the Sturm sequence, hence the query. Since then a colleague, Mr Kent, has done more work (cols 3 and 4) introducing extra degrees of freedom into the centre of the piles. Introducing a horizontal rotational degree of freedom (col. 4) gave a much closer fit. Had we been able to include both  $\theta_z$  and  $\theta_y$  rotations the 'fit' would probably have been exact.

110. This points to the danger of oversimplification. While calculations should be simple, if possible, this fact led to a 15% overestimate. If, as in this case, a safe upper bound is to be established, this could be a serious error.

Table 2. Frequency comparisons

	Sturm sequence (1)	QL method (movement included)		
		$y z$ (2)	$y z \theta_x$ (3)	$y z \theta_z$ (4)
1st mode	79.62	82.15	82.15	80.61
2nd mode	89.71	104.69	104.69	95.57
3rd mode	118.30	126.42	126.42	120.98
Pile mode	?	145.72	145.72	145.71

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111. The explanation is also worth comment. In Fig. 16, the second mode of the piles is close to the high sway mode at about 400 c/min. It is the second mode of the piles which couples with that and forces down the others. Normally one would not look so far away from one's centre of interest for something which will cause 15% variations.

**Mr D. G. McGarey**, British Transport Docks Board

The Paper deals with a problem which is described as unforeseen. Whether or not it was unforeseeable, it is true that it was not in fact foreseen by any of the parties concerned. These parties include John Mowlem & Co., the British Transport Docks Board and Rendel, Palmer and Tritton, as mentioned in the Paper, and also people not mentioned; the consortium of oil companies under the name of 'Humber Oil Terminal Trustees', who are the eventual users and operators of the terminal.

113. Although ultimately any increased costs arising from difficulties and delays are bound to be reflected in the charges paid by the users, no party escaped the consequences altogether. However, the main burden of dealing with this unforeseen and extremely serious trouble fell on Mowlems, and I am glad to have this opportunity of paying tribute to the thorough and painstaking way in which they tackled it.

114. The Paper makes clear that this was by no means a matter of finding an empirical or an *ad hoc* solution. On the contrary, a great deal of care went to making a thorough investigation to establish fundamental causes. Even when the root cause could be described in fairly simple terms, the variations and combinations were complex indeed.

115. I want to underline what is said in § 87. As soon as the implications of the experience at Immingham became apparent I was certain that the whole problem of flow-induced pile oscillation must receive attention as a major research project. At an early stage my Authority approved expenditure on a limited study with our own resources. It soon became clear, however, that with the possibility of full-scale experimentation at the site and the willing co-operation of other interested parties it would be possible to do better.

116. Eventually, with the assistance of a number of contributors, including the National Ports Council, the National Physical Laboratory and Mowlems themselves, we were able to mount a full study under the aegis of CIRIA, as mentioned in the Paper. I am very glad that we were thus enabled to carry the matter forward while facilities were still available and before the relevant expertise had been dispersed. I have reason to think that the CIRIA Report, when published, will show that our efforts have not been in vain.

**Mr G. E. Wild**, John Mowlem & Co.

I should first like to compliment the Authors on a very clear presentation of a very complicated subject. Set out logically, it looks relatively simple, but there was a great deal of research and investigation to be done with remarkably little published information available. The investigations had to be undertaken during construction, and the answers which were wanted immediately had to be taken on whatever was the best information and research available at that time. I should state—and I am sure that Mr Sainsbury would not disagree with this—that in the course of the investigations we made quite a number of false starts. Here it would be only right and fitting that I should pay a very sincere tribute to the patience and understanding of our clients, the British Transport Docks Board, to their clients, Humber Oil Terminal Trustees, and to their consulting engineers, Messrs Rendel, Palmer and Tritton, and that I should express thanks for their help which they rendered in all these investigations.

118. I do not want to deal at any length with the practical problems, but I would like to make three points. The first concerns crossflow vibrations; they are difficult

to deal with in construction, but they are not new. However the in-line vibrations were new but once the mechanics were understood it did not take the Authors long to arrive at methods of dealing with them. The problem which remained was the question of the overall sway of the platforms and dolphins, although really nobody could credit that such large masses of concrete, with so many piles, could move. We went ahead in that belief, and fortunately were proved right, but there is a threshold of some sort there, because the smaller dolphins did in fact vibrate, although in a rotational way. I am sure that the magnitude and influence of damping factors and the question of energy input from these vortices is a field which requires further investigation. From the results of Table 1, it will be apparent that there are a number of other structures which may be close to the borderline.

119. The final point was on the question of whether any relief from the effect of the fast current on the piles could be expected from the interplay of one pile with another; whether the interference of the piles would slow the current down so that the piles towards the downstream end of the structure would not vibrate. The evidence of the cooling towers to which Mr Sainsbury has referred suggested that the possibility had to be discounted. There was some evidence in the NPL experiment that there was sufficient interference to reduce the speed but it was not noticed at the time. We assumed that we had to cater for the full speed all the way through the berth, possibly speeded up by the presence of a ship alongside the berth, and we took a very painful decision that all the piles under the berth had to be braced. There I think we have been proved wrong. In fact, this complex of piles slowed up the current so much that I am convinced that most of the bracing which had been put in under the berth was unnecessary. But decisions have to be taken on the evidence available at the time.

**Mr D. H. Cooper**, British Transport Docks Board Research Station

Further experimental work has been carried out at Immingham. It might be appropriate, therefore, at this stage to summarize its scope. The successful completion of the jetty at Immingham did not lessen the need for the tests since the Authors' findings were thought at that time to be probably unique to the site—§ 25 makes this point clear.

121. A rig was constructed on the jetty, and three test piles of 18, 24 and 30 in. dia. were specially driven and fitted with accelerometers. Flow speeds were measured in front of the piles and a yaw meter recorded pressure fluctuations in the wake of the 30 in. pile. The head of each pile was restrained by means of a capping beam that could be rotated between tests. It was thus possible to reproduce encastrate or pinned conditions at the upper fixity level, or any combination of the two. Perforated shrouds could be lowered around each pile to prevent oscillations between tests.

122. The main objective of the investigation was to establish a better understanding of the mechanics of pile oscillation; the second objective was to provide full-scale data on which model experiments could subsequently be based. The basic result obtained was the comparison of the amplitude of oscillation with flow speed for both in-line and transverse oscillations.

123. The effect of Reynolds number on the motion and the influence of the angle of the capping beam to the flow direction were also studied, as were the properties of the piles in still water and the effectiveness of the perforated shrouds.

124. The experimental work on site is now completed. The final report which is being prepared for CIRIA will be ready in 1972. It would be wrong to anticipate the findings of this report, but I can say that, in the main, we do not dispute any of the criteria reached by the Authors. Their simplified explanation of the cause of the motion can now be extended considerably. In our opinion, a jetty built to the design parameters of Mr Sainsbury and Mr King would be unlikely to oscillate.

125. One unexpected benefit has resulted from the experiment. Following prolonged observations of the vortex wake, it has been possible to suggest a simple device

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that will reduce and possibly prevent oscillations. This device is at present being considered by CIRIA and the National Research Development Corporation for full patent cover.

**Dr D. E. Wright**, Construction Industry Research & Information Association

The first point I wish to make is a professional one. All who have at heart the proper status of the professional civil engineer will welcome the trend evident in papers in recent years of describing mistakes and difficulties which have occurred during design and construction. It is hard to admit mistakes when they occur, and they can be very uncomfortable to live with while their causes are being understood and remedied. Yet we learn most from our mistakes and there are occasions, I believe, when it is part of our professional duty to share the lessons learnt and so prevent other people from having the same difficulties. I therefore welcome this stimulating Paper and congratulate the Authors on the way in which they have described the many pressing and also intriguing difficulties that they faced.

127. My second point is a technical one. The Authors have recommended that, if possible, designers should develop structures so that the value of the reduced velocity ( $V/ND$ ) for in-line motion is less than about 1.2 and its value for cross-flow motion is less than about 3.5. In § 26 the Authors reflect that the ratio of threshold reduced velocities is about 1:3, whereas the ratio of the velocities at maximum amplitude is about 1:2. There is a dissimilarity between Figs 5 and 6 which could, in part, help to explain this anomaly.

128. In Fig. 6 (showing cross-flow motion of the prototype) the points nestle on the abscissa up to  $V/ND \approx 3.5$  and then climb rapidly, whereas in Fig. 5 (showing the in-line motion) there is very considerable scatter in the region where the curve leaves the abscissa. It would be possible within this scatter to choose a point on the abscissa which yielded a ratio of threshold reduced velocities nearer to 1:2. Do the Authors see any link between the disparity in the reduced velocity ratios noted in § 26, and the difference between Figs 5 and 6 described above?

129. The third of the points I wish to raise concerns the need for future research. On completion of the report on the prototype research programme (mentioned in § 94), the Hydraulic and Public Health Engineering Committee of the Construction Industry Research and Information Association (CIRIA) will consider whether yet further research may be necessary. The aim will be to extract in full the lessons learnt both from the construction difficulties described in the Paper and the prototype research programme for the benefit of those who will design and construct works of this kind in the future.

**Mr R. J. F. Peck**

I join the other speakers in welcoming this very candid Paper which has dealt with the experience concerned in such a clear and easily followed way.

131. My question relates to the method for evaluating the maximum safe velocity for which recommendations are given in the conclusions at the end of the Paper. In equation (12), the equivalent mass must be evaluated, and since it is a function of the fluid displacement of the pile as well as its mass, I wonder if the Authors could indicate how one should allow for that part of the pile which is not submerged. Is it necessary to make an allowance for this?

**Mr I. P. Haigh**, Consultant, Sir Alexander Gibb & Partners

No doubt the Director of CIRIA has reflected on how much easier it was to obtain special contributions to finance research into problems that had not been foreseen and that led to real problems in construction than to find money for research into problems that could be foreseen! The difficulties experienced with the vibrating piles at Immingham were clearly in the first category.

133. Could the Authors provide more information about the relative magnitudes of the transient transverse and drag forces than was given by the phrase 'one degree higher' in § 17?

134. The information given in § 30 about the depth of 'apparent fixity' of a cantilever pile was of interest. Some years ago tests with transverse loadings were carried out on the box piles driven for a mooring dolphin at an oil jetty on the Foyle, to determine this depth below bed level in soft alluvium and boulder clay. They gave, reassuringly, similar results, but they were tests under static loadings. Were the Authors satisfied that with vibrational oscillations the shallow depth of the fixity would be maintained?

135. The Authors are to be commended for their attempt in § 87-94 to develop general design criteria. Full vibration analyses of jetty structures would be a time-consuming and superfluous task, except in rare circumstances; there is much to be said therefore for these simple design criteria for judging when a detailed analysis may be justified. The interesting case in Table 1 is the jetty at West Thurrock; these piles could be at the power station jetty, but there is no report from that site of oscillations.

**Dr Winifred L. Wood**, Department of Mathematics, University of Reading

I read this Paper with particular interest because ever since I first heard of this problem some years ago I have been using it in my lectures as a dramatic illustration of the physical significance of eigenvalues and eigenvectors. As a mathematician I should be interested to know more about the methods used to obtain these.

137. The Sturm sequence method can of course be applied to the set of equations of the form given by the Authors:

$$[K - w^2 M] [\delta] = 0 \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where  $K$ ,  $M$  are symmetric and positive definite because the principal minors  $P_i$  say of  $K - w^2 M$  form the Sturm sequence, and if the result of the forward elimination is an upper triangular matrix  $U$  then  $u_{ii} = (P_i)/(P_{i-1})$ , taking  $P_0=1$ . Thus the number of eigenvalues less than a trial value of  $w^2$  which is given by the number of changes of sign in the Sturm sequence is the same as the number of negative  $u_{ii}$ .

138. However if the QL method referred to in Table 2 is the QL method in ref. 16, this needs to be applied to a symmetric matrix in the standard eigenvalue problem. Hence equation (3) has to be reduced to the standard form

$$A[x] = \lambda[x] \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where  $A$  is symmetric.

139. Could the Authors say what method they employed to reduce the equations to the form (14), and also how they chose the displacements referred to in § 104: 'in the analysis only certain displacements were retained.'

140. Clough<sup>17</sup>, discussing finite element methods which, of course, lead to the same type of equations, states that 'A significant conclusion derived from a large number of dynamic finite element results is that the lumped mass formulation will provide results having any desired degree of accuracy with less computational effort than is required by the consistent mass procedure'. Could the Authors comment on this from their experience? It seems to be directly contrary to the statement made by Zienkiewicz.<sup>18</sup> The Authors mention that they used a lumped mass matrix in some cases and a distributed mass matrix in others and it would be useful to have their conclusions.

**Mr Sainsbury and Mr King**

We wish first to thank Mr McGarey and the other speakers for their kind remarks about the Paper and we look forward with him to the useful and interesting results which we now believe will come from the CIRIA experiment.

## DISCUSSION

142. **Mr Wild** has raised one of the key points outstanding before complete mastery of this subject can be claimed—the vulnerability of heavy structures. We did not know the limiting value of  $K_s$  and the torsional complexities of the dolphin raised innumerable problems. Although the dolphin is a smaller structure than the berth, it is, in terms of deck mass per pile, comparable, so we must not assume that the safety of the berth was earned by a very large margin.

143. There are very difficult problems here and we hope the experiment will contribute some of the answers. One of the main aims is to achieve accurate, full-scale results of pile response; then, so long as we can reproduce these results for a simple pile at model scale and prove the validity of model scale work for this form of excitation, we shall be able to use models to investigate heavy multi-pile structures, though even this may not be easy since full elastic similarity will be necessary to achieve the correct coupling.

144. On the question of the berth bracing, we agree that much of the work was unnecessary. Perhaps the downstream two-thirds of the berth could have been left unbraced, safety coming from the very pronounced reduction in flow velocity through the close grid of piles. Unfortunately, we did not fully appreciate this at the time.

145. **Dr Wright** has drawn attention to Figs 5 and 6 and the unexpected ratio of nearly 3:1 in threshold values of  $V/ND$  compared with the expected ratio of 2:1 in peak values. We do not believe the scatter in Fig. 5 to be relevant; this effect is mainly due to the results from the cantilever piles described as being 'in the wake of other piles' and these points were actually ignored in determining the threshold value. These piles were in an area of extreme turbulence. The 3:1 ratio has emerged from the CIRIA experiment as a point of great interest and we hope in publication of that report to explain its cause.

146. **Mr Peck** has raised an important point in the application of equations (9) and (12). It is necessary to consider the form of equation (1). This is such that the true value of equivalent mass  $M'$  for a pile will always tend strongly towards that value of  $M$  which applies over the length of pile subjected to largest amplitudes. For a pinned headed pile, therefore, there is a negligible error in assuming that the water level reaches the top of the pile; thus the simple value of  $M$  (from equation (3)) can safely be used for consideration of in-line excitation of structures or pinned piles. The agreement with frequencies observed on site was so close that this approximation was used even during the detailed studies of the Immingham piles.

147. If the field of study should happen to be the cross flow motion of cantilever piles then such an approximation could be wildly wrong if the pile projects above the water surface. Fortunately, in this case, the mathematics required to assess  $M'$  are extremely simple since a parabolic deflexion mode can be assumed and equation (1) integrated directly.

149. **Mr Haigh's** question about the ratio of forces acting in the crossflow and in-line directions cannot be answered directly from the work done during the construction of the terminal since no measurements of force were made. The observed differences in amplitude (equations (5) and (6) and § 27) give general support to the remarks in § 17.

149. The assessment of pile fixity level was a point of particular interest, reflecting as it does not only on the vibrational characteristics of the piles but also on other structural properties. There was no evidence of a significant lowering of fixity level due to prolonged oscillation and this has been confirmed by behaviour of the experimental piles. Comparison with these piles indicates, however, that to achieve the reported very shallow levels of apparent fixity a considerable pile penetration is needed.

150. It is not possible to say, without much greater detailed knowledge of the West Thurrock jetty, why in-line vibration of piles was not experienced. It is important to remember that Table 1 was developed for the special purpose of considering berth sway and it could be that the pile lengths for the approachway, where equation (12) would more properly apply, are somewhat smaller.

151. It is pleasing that equations (9) and (12) have attracted interest. They were included because it was felt that a generalized approach of great simplicity would be of value. They are intended only as a preliminary guide however. It would be most unfortunate if people seized on these equations as the one simple thing in the Paper and used them, for that reason, as their sole guide for future work. By definition, they have to be somewhat conservative, so that if designers resort to these equations alone, they will often be moving backwards rather than forwards, which was not what was intended. We hope that with proper use this approach will be of value. It can be made more accurate and more useful if anyone can develop a generalized yet rather more accurate assessment of vibration characteristics. It seems likely that by the end of the CIRIA experiment we shall have exact and reliable information of the hydraulic characteristics, so that if a more accurate expression for the vibrational terms can be devised we might still hope to get close to a simple answer to this difficult problem.

152. Dr Wood has asked for more detail on how the QL method was used. Martin<sup>15</sup> (§§ 99–110) does give reduction details. The actual procedures used were:

REDUC1, TRED2, TQL2, REBAKA

With regard to the displacements chosen, the chief objective was to reduce the matrix size by treating the cap as a rigid body (six degrees of freedom), and it was necessary to assess the influence of the top pile section on the rigid body mass and inertia (particularly the rotational inertia), hence the use of distributed mass matrices. It was felt that since the interest lay in the cap rotation and pile bowstring modes two degrees of freedom per pile at the centre would be adequate. Table 2 shows the error of this decision: provision should have been made for pile second modes by allowing four degrees of freedom per pile.

153. On the question of distributed or lumped mass matrices, our experience (§ 75) was that lumped mass on two modes per pile gave adequate results. This was of course for a particular structural type and the lower frequencies. Distributed mass was valuable in the QL approach to obtain sensible inertias. The most important point is that the matrices must not be too small, thereby distorting results. For general purposes and finding the overall picture the Sturm sequence with lumped mass has the advantage of simplicity and ease of handling large enough matrices to ensure accuracy, although it may be costly. If a more detailed study is required the more sophisticated approaches may be cheaper in the long run, but the Sturm sequence results are valuable for checking on correct modelling and guidance on matrix sizes. We believe that the greatest requirement is to provide sufficient degrees of freedom on each member to prevent it from distorting the mode shape (and frequency) by its own inadequate representation.

## References

17. GALLAGHER R. H., YAMADA Y. and ODEN J. T. (eds). *Recent advances in matrix methods of structural analysis and design*. University of Alabama Press 1971.
18. ZIENKIEWICZ O. C. and CHEUNG Y. K. *The finite element method in structural and continuum mechanics*. McGraw-Hill, London. (Revised first impression, 1968, p. 172.)

## Errata

$$\text{Equation (1) (p. 275): for } M^1 = \frac{\int_0^L M_y^2 dx}{\int_0^L y^2 dx} \quad \text{read } M^1 = \frac{\int_0^L M_y^2 dx}{\int_0^L y^2 dx}$$

Fig. 16. (p. 296). Centre line: for '  $\delta_z \theta_x \delta_y$  piles fundamental frequencies  $\delta_x \theta_x \theta_y$ ' read '  $\delta_z \theta_x \delta_y$  piles fundamental frequencies  $\theta_z \delta_y \theta_x$ '.