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NON-LINEAR ANALYSIS OF THE SEISMIC BEHAVIOUR OF MODERATE HEIGHT CONCRETE GRAVITY DAMS

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ABSTRACT

A methodology is described for using standard commercial finite element codes to perform a non-linear seismic analysis of a concrete gravity dam, incorporating non-linearities in the dam and foundation, foundation-structure interaction, radiation damping and fluid-structure coupling. The methodology is applied to the study of moderate height (up to 60m high) concrete gravity dams subjected to moderate level seismic motions. Shaking table studies of carefully scaled models are also described.

KEYWORDS

Non-linear analysis; gravity dams; moderate seismic loading; shaking table modelling.

INTRODUCTION

Research into the seismic behaviour of concrete gravity dams tends to focus on large dams over 100m high, the Pine Flats and Koyna dams being two common cases that are studied. However, there are many smaller dams that pose as great a threat and require as careful consideration of their seismic performance. This is true even for dams in regions of low to moderate seismicity, such as the UK and Northern Europe, since it is now recognised that the extreme seismic event in such regions could cause significant damage, especially to older dams.

In the UK, recent seismic hazard studies have estimated the 1 in 10,000 year event to be around Magnitude 6.0, with peak horizontal ground accelerations of the order of 0.3g. In 1991, the cM5.0 Bishops Castle earthquake, on the border between England and mid-Wales, shook a number of dams in the vicinity (there was no reported damage) and caused minor damage to older unreinforced masonry properties in the towns of Shrewsbury and Wrexham about 20-30 km from the epicentre. This event reinforced the growing view that existing and new dams in the UK should be assessed for seismic loading. The tallest gravity dam in the UK is about 60m high and was built of mass concrete in the early 1960's, with no special provision for seismic loading.

As few previous research studies have focused on dams up to 60m high in regions of low to moderate seismicity, there is a need to establish a picture of their likely behaviour and to ensure that methodologies and principles developed for larger dams are relevant to smaller dams. In view of the relatively moderate extreme event, rigorous analytical studies would be too costly for all but the most hazardous dams. Detailed research studies of a typical dam configuration would give practising engineers a useful insight into the problem. In addition, guidance on appropriate analytical tools would be of value. This paper presents an overview of ongoing research that addresses these problems.

The research programme aimed to develop non-linear analytical methods, incorporating dam-foundation-reservoir interactions, and to evaluate these methods against shaking table and full-scale dynamic experiments. The non-linear analysis would be applied to a typical 60m high dam and conclusions drawn as to the latter's potential behaviour, including failure mechanisms, under typical UK seismic loading. This would indicate the scale of the problem and give guidance on modelling issues.

ANALYTICAL METHODS

Non-linear analysis of concrete dams presents a number of problems, in particular the modelling of:

- input motions,
- foundation-structure interaction,
- radiation damping,
- fluid-structure coupling,
- non-linear material behaviour of concrete and rock.

Elastic analyses using such programs as EAGD84 have demonstrated the importance of modelling foundation-structure interaction, including radiation damping, as well as fluid-structure interaction. Radiation damping arises from the semi-infinite boundaries and wave propagation characteristics of the foundation and fluid domains. Rigorous elastic solutions of this problem are possible, but they generally operate in the frequency domain, which is unsuitable for non-linear problems. The only avenue for non-linear analysis is a time stepping solution, but incorporation of infinite boundaries in such models is still far from straightforward. Fluid-structure modelling is now reasonably well understood, but again the most common rigorous solutions operate in the frequency domain.

The application of the input ground motion is problematic with an infinite boundary. Furthermore, the ground motion is usually defined at the surface, rather than at some depth in the foundation rock. A solution is needed that can cater for both of these problems.

The non-linear, dynamic behaviour of prototype dam concrete is poorly characterised. The large aggregate sizes often used in such concrete limit the scope for laboratory testing. Very large specimens are necessary to overcome the aggregate size problem, but these require massive and expensive dynamic test machines of which there are few in the world. There is scope for international co-operation to fund a suitable materials test programme. The lack of material data forces the uncertain extrapolation and application of material models developed for more common structural concretes with smaller aggregate sizes.

Finally, non-linear behaviour occurs in the foundation rock as well as in the dam. Indeed, the foundation is the least well-defined part of a dam, yet it is the part through which all the reaction forces must pass. Analytical solutions incorporating non-linear zones in the foundation are difficult; most non-linear analyses of gravity dams conveniently assume a rigid foundation, but it is well-known that foundation flexibility has an important influence on the response of the dam itself.

Given these limitations, great care must be taken in interpreting a non-linear analysis of a concrete gravity dam. However, such analyses can still give a useful insight into the potential seismic behaviour of a dam. With good reason, dam engineers tend to treat the results of any analysis with a healthy scepticism, and this should be especially so for non-linear seismic cases.

A primary objective of the current research is to develop acceptable non-linear analytical methods that meet the immediate needs of practising engineers wanting to explore the gravity dam problem. As most dam engineers have access to commercial finite element packages such as ANSYS, ABAQUS, LUSAS and ADINA, which have powerful non-linear capabilities, methodologies have been sought that can exploit these tools rather than requiring the development of specialised codes. The package used in this study was SOLVIA, a commercial derivative of the widely used ADINA code.

Radiation damping

Simic and Taylor (1995a) reviewed a large number of radiating boundaries suitable for incorporation in a time history analysis. They showed that a simple viscous boundary, although not transmitting all radiating waves perfectly, catered for the bulk of the energy loss and, in view of its simplicity, was an adequate solution. Fig. 1 shows the finite element model used in most of the studies. The viscous boundary was implemented using the general, 2-D, 4-noded plane element in SOLVIA, which allows the viscous damping properties to be stated explicitly. All the shaded elements immediately adjacent to the external boundary of the foundation were assigned appropriate damping properties. Full details are given by Simic and Taylor (1996). Simic and Taylor (1995a) discussed the optimum finite element discretisation for modelling foundation-structure interaction and radiation damping. An important conclusion was that the foundation should extend a minimum of three dam heights away from the dam.

Non-linear foundation zone and application of input motion.

The main non-linear behaviour in the foundation rock is likely to occur in most typical cases in the zone immediately beneath the dam. There is, therefore, little point in the foundation rock being modelled as a non-linear material in its entirety. The finite element model can be divided into two sub-structures, one non-linear covering the dam and non-linear foundation zone, the other covering the elastic part of the foundation rock. As the non-linear zone is embedded in the elastic zone, any substructuring approach strictly should handle the so-called wave scattering problem at the interface between the two substructures.

If radiation damping is to be modelled, both the non-linear and elastic portions of the foundation must have mass. The latter fact, and the presence of a viscous boundary, present a problem with respect to the application of the input motion. If the input accelerations are applied at the external boundary, they will be largely absorbed by the viscous layer. Also, the mass of the foundation will affect the propagation of any incoming waves. To overcome this problem, Simic and Taylor (1996) adopted a modified form of Clough's boundary input scheme in which the input motion was applied only to the non-linear foundation and dam substructure. The input motion was taken to be the surface motion defined by response spectra proposed for the UK. As the degree of embedment of the dam and non-linear foundation zone was relatively small, the influence of the scattering problem was considered unimportant within the context of the many other limitations of the analysis. By making this assumption, it became a simple matter of manipulating the mass matrices of the non-linear portion of the model, using the standard commands in the SOLVIA program, to generate the required input forces. This input procedure was compared with an equivalent EAGD84 model for a purely elastic analysis. The computed responses of the dam showed negligible differences, thereby supporting the view that the scattering problem, due to the embedment of the dam and non-linear foundation zone, was not significant.

The proposed foundation and input motion modelling procedure deals with radiation damping and foundation-structure interaction in a straightforward manner that readily can be implemented in many common finite element packages through their normal input command structures.

Fluid-structure coupling

Recent research at Bristol University has explored the use of fluid finite elements in which the nodal variable is displacement rather than pressure. Such Lagrangian elements are known to suffer from spurious zero-energy modes. Greeves and Taylor (1992) have investigated a field consistent formulation that tends to stabilise these modes, while also modelling free-surface effects such as sloshing. Being displacement based, such elements are easy to incorporate in standard finite element codes, but further validation work is necessary before they can be used with confidence. Forced excitation studies of a 57m high gravity are in progress to establish a detailed database of the dynamic responses of the reservoir and dam to facilitate the validation of the fluid element.

For most gravity dams less than about 50-60m high, the natural frequencies of the dam and reservoir are sufficiently separated for radiation damping through the reservoir not to be significant. This implies that fluid compressibility can be neglected and, consequently, an added mass representation of the reservoir effects can be a simple alternative if suitable fluid elements are not available. The limitations of the added mass approach must be recognised but, in the context of moderately high dams subject to low amplitude seismic inputs, it can be a reasonable first approximation (Greeves and Taylor, 1992).

Non-linear material modelling of concrete

Any non-linear constitutive model of dam concrete must cater for the effects of tensile cracking. A review of concrete models concluded that fracture mechanics based models were the most promising, but needed further development and were not readily available in many standard codes. Two other classes of constitutive models, namely smeared cracking and plasticity models, were more commonly available in standard finite element codes. The review concluded that smeared cracking models were acceptable for modelling concrete gravity dams, providing care was taken in discretising the finite element mesh. A comparison of a smeared cracking model and a plasticity model applied to a gravity dam, which was subjected to a range of hydrostatic loads, showed how the two tend to predict very different failure modes (Simic and Taylor, 1995b). The plasticity model lead to widely distributed yielding, while the smeared cracking model predicted localised cracking that was more consistent with crack propagation through a brittle material. Simic and Taylor (1996) discussed the application of a typical smeared crack model that is available in codes such as ADINA and SOLVIA.

Non-linear material modelling of foundation rock

This is even more complicated than for concrete, owing to the often jointed nature of the rock. A possible approach is to adopt a smeared cracking concrete model with parameters adjusted to suit the rock. In such a case, the rock would be assumed to be homogeneous initially, and cracks would form and propagate as in the concrete of the dam. Clearly, pre-existing joints in the foundation could have a significant influence on the development of foundation failure mechanisms, but accounting for these may be difficult if using a standard finite element code.

PARAMETRIC STUDIES

A series of studies of a typical 60m high gravity dam (Fig. 1), subjected to synthesised input motions enveloping the UK hard rock response spectrum, was reported by Simic and Taylor (1996). The input motion had a strong motion duration of about six seconds and peak accelerations of 0.3g and 0.2g horizontally and vertically, respectively. The studies used a finite element model incorporating the analytical concepts discussed above. For simplicity, the reservoir effects were represented by a Westergaard added mass distribution. The dam and non-linear portion of the foundation were represented by a smeared crack model. The response was computed for foundation elastic moduli of 5, 10, 20 and 40 GPa and a concrete modulus of 24 GPa. The tensile strength of both the rock and concrete was taken to be 1/10,000th of the elastic modulus. Static loads were applied to the dam prior to the dynamic loads.

Fig. 2 shows the influence of the foundation stiffness and strength on the pattern of cracking. For the weak 5 GPa case, cracks propagated almost vertically into the foundation from the upstream heel. As the foundation stiffness and strength increased, the inclination of the cracks rotated towards the horizontal until, for the 20 GPa case, they were horizontal and passed through the rock immediately beneath the dam. For the 40 GPa case, representing a very stiff foundation, the horizontal cracks propagated through the weaker concrete. Cracking on the upstream and downstream faces was more pronounced but only penetrated a few metres into the dam. It was encouraging that the induced cracking was not serious. The analytical studies demonstrated the methodology by which a non-linear analysis of a concrete gravity dam could be undertaken using a standard finite element code.

SHAKING TABLE STUDIES

To complement the analytical studies, carefully prepared 1/30th scale physical models of a 30m high dam have been tested on a shaking table (Mir and Taylor, 1995). The models were constructed from a sand-plaster material having the correctly scaled stress-strain properties. Dynamic reservoir effects were modelled using lead masses placed in contact with the upstream face of the model, while a small water filled tank was used to provide the hydrostatic load. The sand-plaster material turned to a slurry when in contact with water, so the reservoir was separated from the dam by a thin rubber membrane. As a consequence, water was not able to penetrate into any cracks induced in the dam. The dam model was epoxy bonded onto a rigid steel plate that was attached to the shaking table platform. No foundation rock was modelled. Earthquake motions were applied only in the horizontal upstream-downstream direction.

A wide range of input motions was used on a total of four models. All the models failed by propagation of a horizontal crack from the upstream heel into the model concrete. In no cases of earthquake input, which reached a peak table acceleration of 1.2g, did the crack propagate over the full width of the dam (from upstream to downstream). Only when an accidental transient of over 3.5g was applied did the crack extend over the full width. Under combined static and normal earthquake loading, the dam was able to tilt downstream, forming a compressive stress block in the vicinity of the downstream toe that was sufficient to inhibit further propagation of the crack. The tests compared favourably with finite element analyses, giving a degree of confidence that catastrophic collapse of a prototype dam would be unlikely in the postulated 1 in 10,000 year UK earthquake.

A further series of tests of a rigid gravity dam model explored the potential for sliding and overturning if a crack extended over the full width of the dam (Mir and Taylor, 1996). The study showed that overturning was not a credible failure mechanism, and that simple sliding block analyses and more sophisticated finite element contact surface elements both gave good predictions of the measured slippage.

CONCLUSIONS

Non-linear analysis of concrete gravity dams is possible using commercially available finite element codes. Although such analyses have important limitations, if treated with caution they can provide a useful insight into the potential failure scenarios of a dam.

Initial studies of a typical 60m high gravity dam subjected earthquake motions representative of a magnitude 6.0 intra-plate event, indicate that catastrophic collapse is very unlikely, although some cracking in the dam and foundation could be expected.

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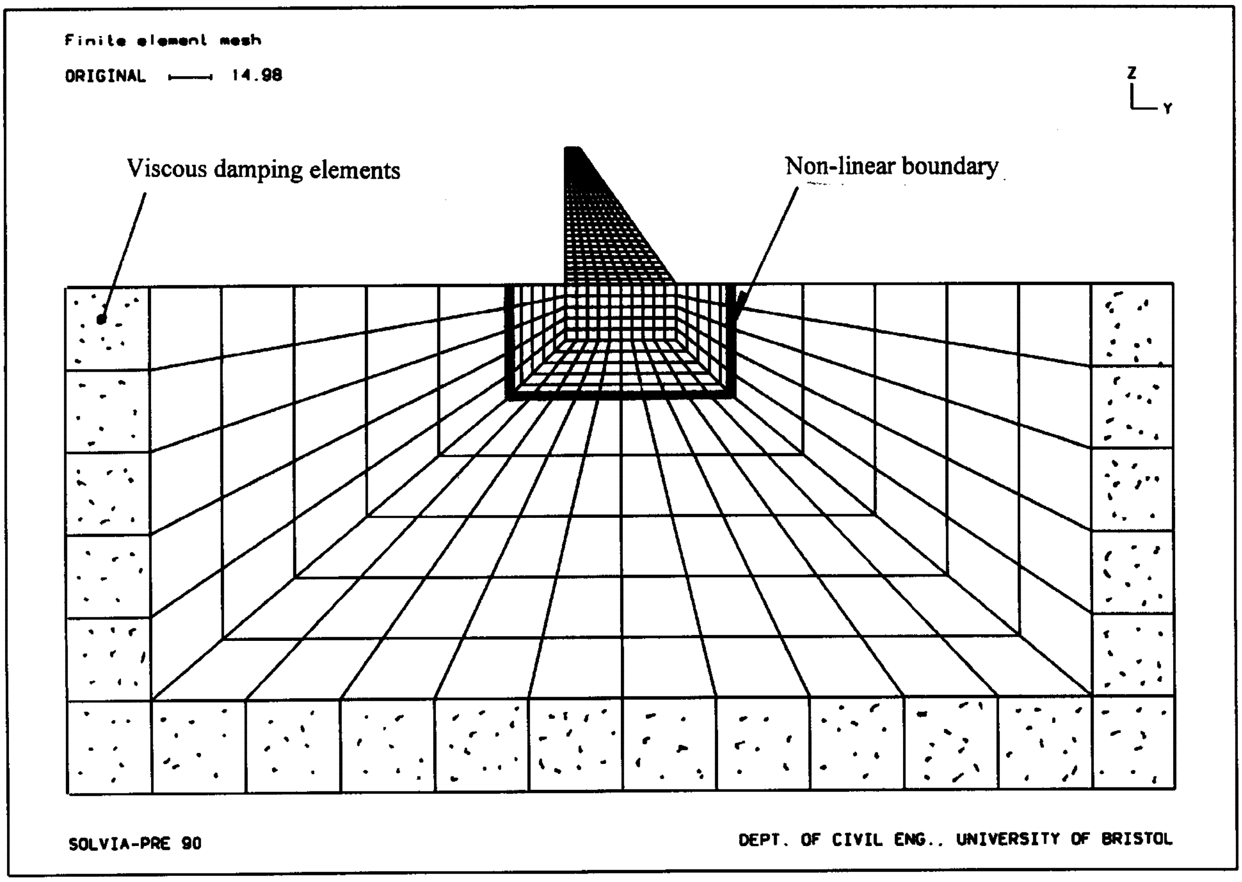

Fig. 1. Finite element mesh for 60m high dam case study

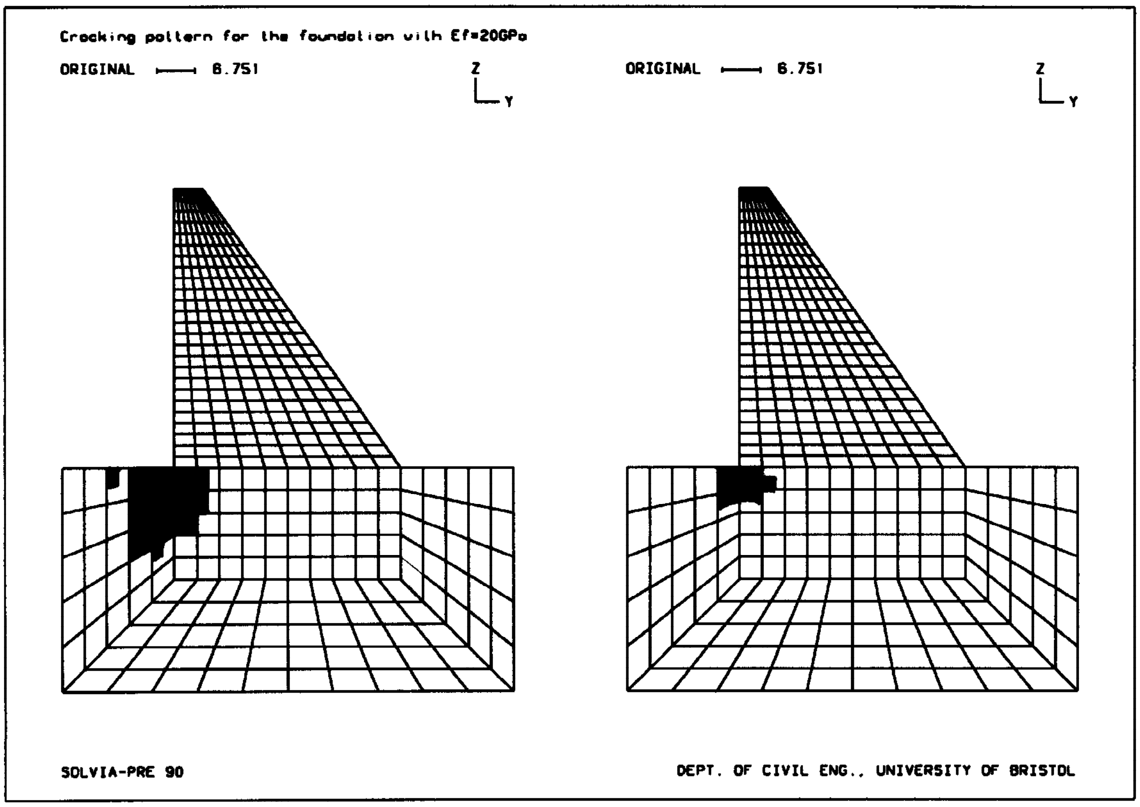

Fig. 2a. Crack pattern for 5 GPa foundation

Fig. 2b. Crack pattern for 10 GPa foundation

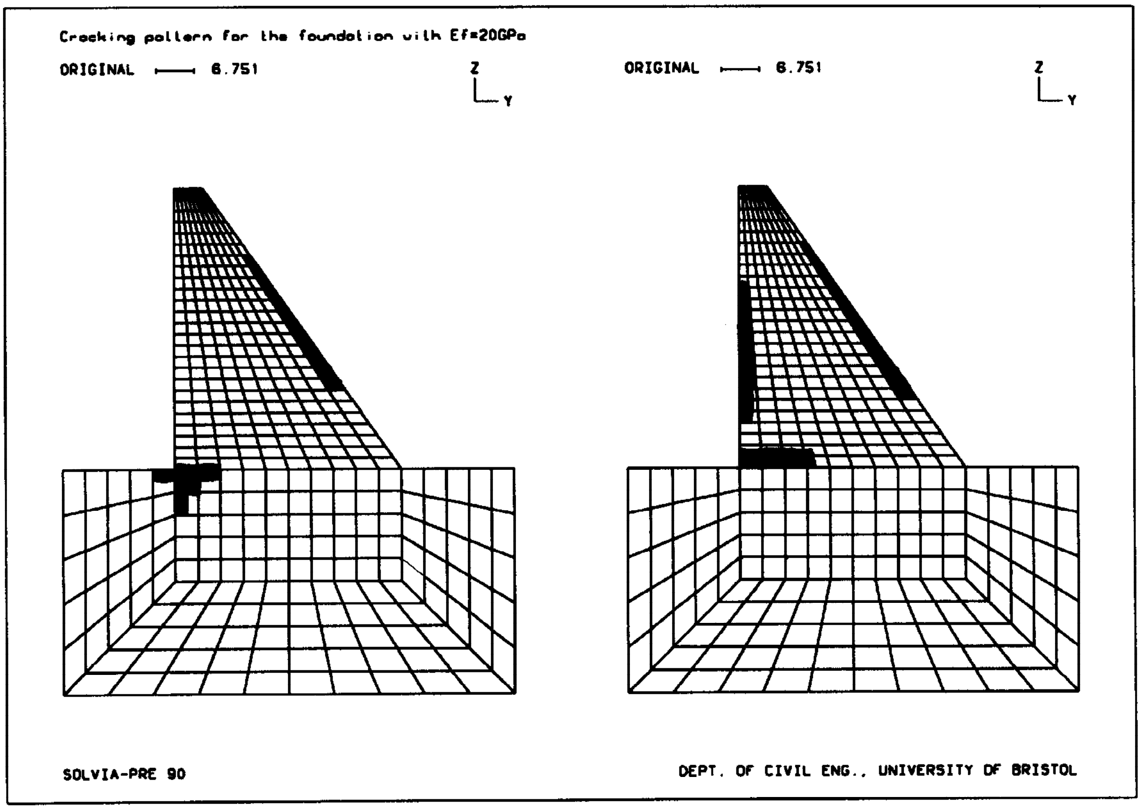

Fig. 2c. Crack pattern for 20 GPa foundation

Fig. 2d. Crack pattern for 40 GPa foundation