DISCUSSION

Explosive compaction: design, implementation and effectiveness

W. B. GOHL, M. G. JEFFERIES, J. A. HOWIE and D. DIGGLE

W. H. Craig, *University of Manchester*

The authors have demonstrated with their video clips that a picture can indeed be worth a thousand words. Following the detonation of subsurface explosions a volume of the ground liquefies and the pore fluid seeks a route to the surface. The process of pushing an instability, through some fingering mechanism, to the surface can clearly take some considerable time—of the order of 2 mins. The subsequent outrush of soil and liquid from a pipe in an unpredictable location can be quite violent, and can also last for some time. While the overall result may be densification and consolidation of the ground, the pipe outlet itself may remain as a very loose zone. Is there any evidence of this from post-detonation probings?

Authors' reply

The discussor has identified a potential source of loose zones within the densified mass. As noted, loose zones may be created by the flow of water displaced by reduction in void ratio due to densification. However, the largest volume changes occur during the first pass of explosive compaction, and the site illustrated in the video (Kelowna) was extremely loose (apparent relative density of about $D_r \sim 25\%$), which emphasised this aspect of the ground response.

The videos were shown to make the point that explosive compaction is really an induced consolidation, at least initially, with density change following explosive detonation on a very different and independent timescale. Attempts to simply correlate the achieved final density with the explosive weighting miss an important mechanism. However, the video perhaps overemphasised the prevalence of piping.

Large-scale liquefaction is commonly associated only with the first few shots of the many used in compacting a site, and even then only with the very loose site. Typically we detonate only 9–12 holes in a single shot, and the first pass will correspondingly involve many shots to cover the entire area of the site. These later shots induce excess pore pressures, but settlements are reduced and the compaction of the site becomes more uniform. Wide-scale liquefaction is simply not seen then—indeed this might even be taken as proof of adequacy of treatment if liquefaction was the primary concern. Settlements may be induced some distance from the shot area once the soil in the area settling has been disturbed by its own shot. Typically after two or three passes of blasting the zone of settlement extends at approximately a 45° line from the deepest depth of blasting.

Compaction uniformity is important because many compaction projects are related to liquefaction concerns, and liquefaction (and cyclic mobility) is controlled by the looser pockets in the soil. This control by the loosest end of the spectrum appears to have been first reported on the basis of centrifuge studies of the Oosterschelde closure caissons (Rowe and Craig 1976). Subsequent numerical studies have reinforced the conclusion in the case of cyclic mobility in hydraulically placed sand (Popescu *et al.*, 1997) and static liquefaction of hydraulically placed sand. It appears that the controlling behaviour (*characteristic property* in limit states jargon) is dominated by the loosest 10–20% of the deposit.

Being aware of the importance of loose pockets, we have

been more concerned with the collapse of material into the expansion cavity caused by the explosive charge, primarily because there is always a regular grid of such features, and these features are always there even in the last stages of compaction. Fig. 6 of the paper showed the approximate 97.5th and 2.5th percentile limits (95th percentile range) of penetration resistance of compacted soils because of this concern for the variation in soil properties. Fig. 8 adds to this plot by presenting the variation penetration resistance encountered when testing a fill using a regular grid. As can be seen, there are substantial fluctuations in penetration resistance on a scale of a few metres.

Figure 9 shows penetration resistance for CPT soundings targeting the explosive zone, with the results of soundings 0.4 m, 1.4 m and 3.0 m from the blast borehole being shown. The depths of the explosive charges in the borehole are also indicated. Comparing Fig. 9 with Fig. 8, there is some support for a conclusion that there may be a looser zone within about a 1 m radius of the detonated borehole. However, the data at 9 m depth are less clear on this point (although at this depth we have less certainty in actual distance because of CPT deviation in the ground). Also, there is not a clear correlation with proximity to the charge because the loosest zone at 0.4 m radius appears about midway between the two upper charges. On the other hand, the fluctuation between the soundings at 1.4 m and 3 m radius are entirely consistent with the general pattern of fluctuations seen as a whole as plotted on Fig. 8.

Fig. 8. Illustration of soil variability when tested by CPT on a regular grid (densification zone started at 5 m depth)

Fig. 9. CPT resistance adjacent to blast hole

Recent numerical simulations suggest that the important feature is the degree to which loose zones are aligned along the direction of possible shear zones; vertically inclined looser columns are unlikely to be a concern in this regard. Nevertheless, we have always used at least two passes in production explosive compaction to compact loose zones remaining after the larger settlements of the first pass and to improve the uniformity of the densified mass.

In conclusion, while piping in the early stages of explosive compaction is often dramatic, its occurrence is a clue to the nature of explosive compaction rather than a cause for concern for the results of properly executed work. Loose columns do appear to arise around the explosive charges themselves, and this is one reason to limit charge sizes in favour of more passes. Too much explosive is not a good thing as far as effective compaction is concerned. Our work has used the criterion that about 85% of the soil should be denser than the desired target as a way of reasonably accommodating the concerns about property variation.

REFERENCES

- Popescu, R., Prevost, J. H. & Deodatis, G (1997). Effects of spatial variability on soil liquefaction: some design recommendations. *Géotechnique* **47**, No. 5, 1019–1036.
- Rowe, P. W. & Craig, W. H. (1976). Studies of offshore caissons founded on Oosterschelde sand. In *Design and construction of offshore structures*, Institution of Civil Engineers, London, 49–55.