A symposium on Recent Advances in Geotechnical Centrifuge Modeling was held on July 18-20, 1984 at the University of California at Davis. The symposium was sponsored by the National Science Foundation's Geotechnical Engineering Program and the Center for Geotechnical Modeling at the University of California at Davis.

The symposium offered an opportunity for a meeting of the International Committee on Centrifuges of the International Society for Soil Mechanics and Foundation Engineering. The U.S. participants also met to discuss the advancement of the centrifuge modeling technique in the U.S. A request is being transmitted to the American Society of Civil Engineers to establish a subcommittee on centrifuges within the Geotechnical Engineering Division.
CENTRIFUGE MODELLING OF ARTIFICIAL SAND ISLANDS IN EARTHQUAKES

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1. Introduction

Increasingly over the past decade, artificial islands have been constructed for various purposes, most having been constructed in less than 13 m of water with relatively unprotected slopes and with short design lives. However, as oil and gas exploration and production and as port expansion move to deeper waters and the need for more secure and economical designs for such islands develops, more complex forms of island construction have evolved, such as the use of sand-filled caissons on submarine berms, Fig. 1. Where artificial sand islands are constructed in seismically active regions, the behaviour of these soil structures in earthquakes has to be considered. Little quantitative data is currently available on the response of artificial islands to earthquakes, one of the better known sets of data being the pore pressure and acceleration records collected from Owi Island No. 1 in Tokyo Bay during the Chiba earthquake (Ishihara et al., 1981). This paper describes the results of two centrifuge model tests carried out using the Bumpy Road Facility at the Cambridge Geotechnical Centrifuge (Schofield, 1981). In these test, the artificial islands were modelled by two-dimensional embankments in fine sands submerged in silicone oil; further development is now taking place with earthquake tests on three-dimensional circular island models. Rigid steel plates placed on the crest of the embankments represent surcharge on prototype islands, Figs. 2. Both models were tested at a centrifuge acceleration of 40g.

2. Modelling Requirements and Prototype Representation

2.1 Model Scale

A summary of the scaling relationship for geotechnical centrifuge model tests with earthquake shaking is as follows:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Ratio of Model to Prototype</th>
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<tbody>
<tr>
<td>Length</td>
<td>1/N</td>
</tr>
<tr>
<td>Velocity</td>
<td>1</td>
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<tr>
<td>Acceleration</td>
<td>N</td>
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<td>1/N^2</td>
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<td>N</td>
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At prototype scale, there are regions of the island in which excess pore pressure gradients lead to significant pore water diffusion in periods of time equal to the duration of the event, in this case an earthquake. In the absence of inertial effects, it would have been usual to scale times by a model scale factor of $1/N^2$ in order that time factors for consolidation or swelling processes in compressible ground should correspond in model and prototype. If water had been used as the model pore fluid in these two models, it would have been appropriate for the duration of the model event to be only $1/N^2$ times that of the prototype event. This is incompatible with the requirement that the model event should have a duration of $1/N$ times that of the prototype event in order to scale inertial effects correctly. So the time factors for the model were altered by replacement of water by a more viscous pore fluid: in this case the model pore fluid was 42 centistokes silicone oil to correspond with a model scale factor of approximately 40.

It has been shown that in flow regimes for which Darcy’s Law is applicable, diffusion time is directly proportional to pore fluid viscosity (Terzaghi and Peck, 1967), so that the time distortion factor mentioned above can be eliminated by choosing a pore fluid which is $N$ times as viscous as water. Muskat (1946) noted that Darcy’s Law is applicable to laminar flow regime with sufficiently low Reynolds number, a requirement which has been found to be satisfied by prototype flow in silt through to medium sand (Lambe and Whitman, 1969). For Darcy’s Law to be valid for centrifugal models, the same criterion have to be satisfied. Let

$$Re_p = \left( \frac{\rho_v v_p d_p}{\mu_p} \right)$$

and $$Re_m = \left( \frac{\rho_v v_m d_m}{\mu_m} \right)$$

in which $Re_p$, $\rho_v$, $v_p$, $d_p$ and $\mu_p$ are the prototype Reynolds number, pore fluid density, apparent velocity, effective pore size and prototype pore fluid viscosity, respectively; and $Re_m$, $\rho_v$, $v_m$, $d_m$ and $\mu_m$ the corresponding model quantities. Then

$$\left( \frac{Re_m}{Re_p} \right) = \left( \frac{\mu_m}{\mu_p} \right) \left( \frac{v_m}{v_p} \right) \left( \frac{d_m}{d_p} \right) \left( \frac{\mu_m}{\mu_p} \right)$$

If the same soil is used in model and prototype, $d_m/d_p = 1$. Moreover, density of silicone oil is approximately equal to that of water so that $\rho_m = \rho_p$. If the viscosity of the silicone oil is adjusted so that $\mu_m = N \mu_p$, then Eqn. (3) becomes

$$\left( \frac{Re_m}{Re_p} \right) = \left( \frac{v_m}{v_p} \right) (1/N)$$

In the flow regime in which Darcy’s Law is valid, the apparent velocity

$$v = (k/\mu)(dh/ds)$$

where $k$ is a constant of the porous medium, $\mu$ the pore fluid viscosity and $dh/ds$ the hydraulic gradient. hence

$$\left( \frac{v_m}{v_p} \right) = \left( \frac{\mu_m}{\mu_p} \right) \left( \frac{dh/ds}_m}{dh/ds}_p$$

$$= (1/N) \left( \frac{dh/ds}_m}{dh/ds}_p$$

In scaled centrifuge models, $(dh/ds)_m = N(dh/ds)_p$ so that

$$v_m/v_p = 1.$$ Hence

$$\left( \frac{Re_m}{Re_p} \right) = 1/N$$
Since \( N \) is invariably greater than 1, \( \text{Re}_m \) is always less than \( \text{Re}_p \). Thus, provided the prototype flow system is laminar and therefore obeys Darcy's Law, scaling of diffusion time by increasing pore fluid viscosity may be validly applied as it results in a lower Reynolds number and therefore preserves the laminar flow regime.

2.2 Model Materials and Form

The main purpose of the test reported here, as also of the succession of other studies on the Cambridge Geotechnical Centrifuge was to study the mechanics of problems in general and not only of a succession of different sites with different soils (Kutter, 1982, Dean and Schofield, 1983, Schofield and Venter, 1984). In the majority of previous tests, standard sand and clay have been used allowing comparisons of results in different studies. However, some tests have been undertaken using soils from specific sites (Schofield and Venter, 1984).

The models were constructed of Leighton-Buzzard B.S. 52/100 fine sand and had a height of 90 mm, crest width of 200 mm and slopes of about 1 in 3. Forty two centistokes silicone oil was used as the model pore fluid. The prototype problem is a flat crested submerged embankment of the same sand, with a height of 3.6 m, crest width of 8 m and slopes of about 1 in 3. Mild steel plates of 5 mm, 10 mm, and 20 mm thicknesses were used for model surcharges at different stages of the tests. These correspond to average prototype surcharge loadings of about 15 kPa, 31 kPa and 61 kPa, respectively.

3. Model Preparation Method

The model was constructed at 1 g and model preparation procedure follows largely that developed and used by Dean (1983), with minor modifications. As shown in Fig. 2, the model was constructed on a sloping concrete base which was bolted to the base of the container, the 1 in 40 slope of the concrete base being designed to account for the loading imposed by the Earth's gravity field on the model when the latter is in centrifugal flight at 40 g. The model preparation method consists of the following stages:

(a) Forty two centistokes silicone oil was de-aired so as to prevent air bubble formation in the model embankment. This was achieved by drawing it into a vacuum chamber and leaving it under vacuum for at least 24 hours.

(b) Formworks were used to shape the embankment during model preparation and to minimise risk of damage to the model when the package was being moved around. As shown in Fig. 3, the formworks consisted of two major sets of components, as follows,

(i) Two trapezoidal arches which acted as the main load bearing elements of the formworks.
accelerometer) and is taken to be that actually applied to the model. $K_{out}$ is calculated by the formula

$$K_{out} = 50 \frac{(a_{max}+a_{min})}{(Ng)}$$

where $a_{max}$ and $a_{min}$ are the maximum and minimum values of acceleration measured by the reference accelerometer. $K_{out}$ is generally quoted as less in long-term records than in short-term records. This is because less sampling points are used over the time of the earthquake, so the actual maximum and minimum values are usually missed. In the discussion below, the short-term value is taken to be the relevant one.

The time records are plotted as a sequence of horizontal traces, the horizontal axis being labelled in model time, equivalent prototype time can be computed by multiplying model time values by the g-level, that is 40. On the right hand side is the name and number of the device (ACC for accelerometer, PPT for pore pressure transducer) as well as the scale in engineering units per cm. Acceleration is presented in percent strength and pore pressures in kPa. Since both these quantities are preserved in prototype and model, the figures may also be taken to be prototype values. On the left hand side are the maximum and minimum values of the quantity being plotted. Further details on the format of these time history plots can be found in Dean and Schofield (1983).

After these time history plots in Figs. 9 to 15, there are some Lissajous Figures 16 and 17 which are obtained by plotting the record of one transducer against that of another. Phase difference can be estimated from the shape of the figure and some typical plots are shown in Appendix I.

6. Discussion of Results

6.1 Test FHL01, Earthquake 5

Figs. 9 a and b show the short-term and long-term records of a 12s earthquake. The surcharge was a 10 mm steel plate which is estimated to exert an average bearing pressure of 31 kPa in both model and prototype. As the surcharge is rigid, the actual distribution of bearing pressure is unlikely to be uniform. In Fig. 9 a, ACCs 1258, 988, 728 and 1244 show fairly well-coupled motion up to the mid-height of the model. Lissajous Diagrams in Figs. 16 indicate that there is virtually no phase difference between the fundamental frequency components of these four accelerometer records.

All pore pressure transducers show positive response, the maximum being attained by PPT 68 located just beneath the surcharge near the centreline of the model. PPT 2331 located near the slope experienced the minimum pore pressure generation, as would be expected from its proximity to a free-draining boundary.
(ii) Fourteen U-section beams spanning between the two arches were used to maintain the shape of model. These beams were placed as the model was being constructed.

(c) Leighton-Buzzard B.S. 52/100 fine sand was used to form the entire model except the toes which were constructed with B.S. 14/25 and B.S. 25/52 sands to prevent erosion. Along various levels of the embankment, layers of blue-dyed 52/100 sand were poured near the side windows. Upon completion of model construction, these horizontal blue sand layers were pierced by a thin rod to create a set of roughly vertical blue sand traces, which, in conjunction with the horizontal blue sand layers, forms a blue sand grid, Fig. 4. Large scale permanent deformations of the embankment section may be detected by the distortion of this blue sand grid. To ensure full saturation of the model, the sand-silicone oil mixture was de-aired under vacuum before pouring. The de-aired sand-silicone oil mixture was then scooped out in small portions using a plastic beaker which was then immersed in the oil already present in the container and tipped over, thus allowing the sand to pluviate through silicone oil without air bubble formation. In spite of the apparent crudeness of this method, the results for both models were remarkably consistent, as will be seen later. More recently, an improved method of model preparation has been developed, which will be described briefly in Section 7. The average relative density of both models described in this paper was estimated to be between 60% to 70%.

(d) Transducers were placed at appropriate heights in the embankment as sand pouring progressed. Dynamic signals were measured by DJB A23 piezoelectric accelerometers and Druck PDCR 81 pore pressure transducers. Sangamo LVDTs were also used to record surcharge settlement after each earthquake.

Mild steel plates 156 mm long and 200 mm wide were used as model surcharge. As shown in Fig. 2b, three steel plates were arranged lengthwise in series to span the whole length of the embankment. It was felt that this arrangement would reduce interaction between the central segment of the embankment length, where most of the transducers were placed, and the end segments near the windows. To minimise seepage of silicone oil through the gaps between steel plates, thin polyethylene strips each about 2 cm wide were placed beneath the steel plates across the joints, Fig. 2b. Fine sand was glued onto the undersurfaces of the steel plates using araldite to increase friction at the embankment-surcharge interface.

4. Bumpy Road Earthquakes

The workings of the Bumpy Road Facility have been described by Schofield (1981). The model earthquake consists of ten roughly sinusoidal pulses of lateral acceleration on the model container which is transmitted to the model as a base-shaking motion. Typical time records of the base shaking acceleration (see Fig. 5) show that the amplitude of these sinusoidal pulses varies slowly with time. The allowable maximum magnitude of base shaking acceleration that may be applied to the container depends
on the g-level of the test. At 40g, the magnitude of the base shaking acceleration may be varied between 0 and about 16g, the latter being 40% of the centrifuge acceleration and may be considered adequate for strong earthquakes. The frequency and duration of these roughly sinusoidal pulses are about 80 Hz and 125 msecs, respectively, these being equivalent to prototype values of about 2 Hz and 5 secs.

Fig. 6 shows the response spectra of some typical Bumpy Road earthquakes. As will be expected from the roughly sinusoidal variation of the earthquake time records, the response spectra are much narrower than those of natural earthquakes (Newmark and Rosenblueth, 1971). This prevents direct modelling of specific natural or design earthquakes but allows the possibility of modelling of models (Dean and Schofield, 1983) and creates an ideal system to provide dynamic response data for mechanistic studies as well as for verification of analytical and numerical computations.

Analog signals from accelerometers and pore pressure transducers were recorded on a fourteen-channel Racal tape recorder. Tape segments containing the relevant earthquake records were then played back and the analog signals digitised using the FLY14 program developed by Dean (1983).

5. Earthquake Time Records

A total of forty two earthquakes were fired in the two model tests which were designated FHL01 and FHL02; each with three different surcharges, viz 5 mm, 10 mm and 20 mm mild steel plates. Figs. 7 and 8 show transducer positions for each model with accelerometer and pore pressure transducer abbreviated to ACC and PPT, respectively. Owing to the finite size of these devices and their movements within the models during the tests, their exact locations could not be determined. Hence, the positions marked in Figs. 7 and 8 should only be regarded as approximate ones. The results from seven earthquakes are presented and discussed here; a complete collection of the results can be found in Lee (1983). For each of these seven earthquakes, short-term and long-term time records are plotted from Figs. 9 to 15 after one 3-point smoothing pass (see Dean and Schofield, 1983). The data point spacings for short-term and long-term records are 200 microsecs and 1600 microsecs, respectively. The much smaller data point spacing of short-term records allows details of the earthquake event to be captured whilst the larger data point spacing of long-term records means that post-earthquake pore pressure changes can be plotted. Referring to Figs. 9 to 15 again, at the bottom right of each set of time records appears the following information.

(a) G, the g-level.

(b) K_in, which is a control number associated with the testing apparatus. As it does not affect the interpretation of results, it will be ignored hereinafter.

(c) K_out is the earthquake strength measured by an accelerometer mounted on the container (hereafter designated as the reference
6.2 Test FHLO1, Earthquake 8

Fig. 10a shows the short-term time records of a 21% earthquake on the same model with the same surcharge. Again, the record of ACC 728 is very similar to that of ACC 1258 indicating that there is no slip between the base of the model and the concrete base. In fact, over the first 1 1/2 cycles of the earthquake, all acceleration records are very well-coupled to that of the base excitation. From the third to the fifth cycle, the phase difference between ACC 734 and ACC 1225 increases rapidly as illustrated in the Lissajous Diagrams in Figs. 17. It indicates a progressive softening of the soil beneath the surcharge. After the fifth cycle, the acceleration of ACC 734 dropped to a relatively low value as the surcharge is almost completely isolated from the base shaking motion.

This indicates that a drastic development has occurred. If the surcharge were, for example a barge resting on top of a prototype island with wells drilled down into the island for production of gas or oil, at this stage the risers could be sheared off because the barge would begin to slip to and fro relative to the top of the island.

Simultaneously, PPT 68 registered a steady excess pore pressure of 45 kPa, almost 1.5 times the average surcharge pressure on the crest. The soil at the crest is probably liquefied at this stage. PPT 2338 located off-centre at the crest show much lower pore pressure generation than PPT 68, indicating that pore pressure is not uniform across the crest and that only the region around the centreline may have liquefied. Even after liquefaction, ACC 1225 at the crest beneath the surcharge still registered fairly high accelerations. This may be due to the confining effects of the surrounding soil in the off-centre zones which has not liquefied. All this time, PPT 2331 located near the slope registered fairly low excess pore pressure.

In the long-term records of the same earthquake (Fig. 10b), all pore pressure transducers, with the exception of PPTs 2342 and 2332, measured monotonically decreasing pore pressures after the earthquakes. These two pore pressure transducers both were located at mid-height of the model and they highlight the significance of dissipation effects in causing pore pressure increase in regions around the liquefied zone. The delayed failure of the Lower San Fernando Dam in 1971 has been attributed to such dissipation effects (Seed, 1979).

6.3 Test FHLO1, Earthquake 13

Figs. 11 shows the time records for earthquake 13 of strength 33% on the same model with the same surcharge viz. 10 mm steel plates. Instead of the liquefaction phenomenon described in the previous sub-section, ACC 734 measured fairly high acceleration indicating that there is little loss of shear strength in the soil beneath it. Furthermore, ACC 1244 experienced much higher acceleration peaks than that of the base input. PPTs 68, 2342 and 2331 now measured fairly large negative pore pressures for at least parts of the cycles. Only PPT 2332 showed a positive pore pressure response. As will be explained in Section 6.6, this drastic change from the liquefaction behaviour observed in earthquake 8 (see previous sub-
section) may be associated with intense shearing in parts of the model and the dilatancy induced by it.

6.4 Test FHL01, Earthquakes 17 and 24

Figs. 12 show the time records for earthquake 17 of strength 28\% on the same model, but with thicker steel plates, viz. 20 mm. The average surcharge pressure on the crest is now estimated to be approximately 61 kPa. The increase in surcharge leads to positive pore pressure once again, although complete liquefaction of the kind observed during earthquake 8 did not occur. The trend indicated by this as well as earlier earthquakes is that successive earthquakes have caused progressive densification of the soil medium and generation of positive pore pressures, resulting in a material which dilates at large earthquakes. Increasing the overburden pressure once again resulted in the model exhibiting positive pore pressure response. The consistency of this trend is seen again for earthquake 24, a 36\% earthquake on the same model and same surcharge, in Figs. 13. PPTs 68, 2342 and 2331 show large negative pore pressure response indicative of dilatancy. Furthermore ACC 1244 experienced high acceleration amplification relative to the base with strong high frequency component. The effect of seismic history on the behaviour of models in successive earthquakes is a striking feature of these centrifuge test results.

6.5 Test FHL02, Earthquake 14

Test FHL02 was performed with a model with approximately the same cross-section as test FHL01 but with transducers sited at different locations. Figs. 14 show the time record of earthquake 14, a 28\% earthquake, on this model with 20 mm steel plates as surcharge. ACC 1244 on the surcharge again exhibited rapid attenuation of acceleration after the fourth cycle of the earthquake, whilst PPT 2338 located centrally beneath the surcharge registered a high steady excess pore pressure of 78 kPa during the earthquake. PPTs 68, 2335, 2252 and 2331 are all located off-centre along the crest and mid-height of the model. The long-term records of these four pore pressure transducers in Fig. 14 b shows increasing pore pressures after the earthquake as pore fluid drained outwards from the liquefied zone near the centreline towards the free-draining boundaries, that is, the slopes. The similarities between the observations in this earthquake and the liquefaction behaviour for earthquake 8 in Test FHL01 discussed in Section 6.2 is further strong evidence that liquefaction can be modelled on a centrifuge.

6.6 Test FHL02, Earthquake 18

Earthquake 18, a 37\% strong earthquake was applied to the same model and surcharge as that discussed in the previous section. In the short-term time records in Fig. 15, significant amplification in acceleration was observed in ACC 734 located centrally beneath the surcharge. In addition, sharp 'spiky' acceleration pulses with absolute values about 3 to 4 times that of the base excitation were observed in ACCs 728 and 938 located at the shoulders of the model. These spikes occurred in alternating half-cycles and their appearance in the two accelerometer records are out-of-phase, suggesting very strongly an asymmetric
phenomenon. In later tests not reported here, the phenomenon was again consistently observed near the shoulders of the model. Such spikes would be consistent with a jerky motion, with gradual acceleration phases alternating with rapid deceleration phases, leading to large permanent deformation if the acceleration phases occupied a larger part of each cycle than the deceleration phase. There is evidence for such movements having taken place. Fig. 18 shows photographs taken of one slope before and after the test. Substantial bending of the blue sand grid was seen, indicating that intense shearing had taken place in the upper slopes and the shoulders during the experiments.

7. Conclusions

(a) Dynamic modelling using the Bumpy Road Facility has provided novel data for studying mechanisms which are active in a submerged embankment or sand island in an earthquake.

(b) Two such mechanisms can be readily identified.

(i) Positive pore pressure generation in a central zone at the crest, resulting in the extreme case, liquefaction and loss of shearing resistance in the soil beneath the surcharge. Pore pressure dissipation takes place outwards and towards the slopes.

(ii) High acceleration peaks attributed to intense shearing at the upper slopes and shoulders during strong earthquakes.

(c) Data of successive earthquakes on models show a striking influence of seismic history in the response of the models.

(d) Developments of techniques of modelling and of data processing are now progressing rapidly. An improved method of model construction has recently been developed. Briefly, this consists of constructing the model in a dry state, evacuating the air in the model under a vacuum and then using this vacuum to draw in the silicone oil. So far, the results indicate that it has been quite successful and these will be reported in a later paper. Work is now underway to investigate the three-dimensional response of circular islands under similar base shaking excitation.

8. References


Figure 1 Diagram of an artificial island (Cottril, 1981).

Figure 2a Side View of Container and Model

Figure 2b End View of package( AA')
Figure 3 Embankment formworks showing trapezoidal arch and U-section beams.

Figure 4 Blue sand grid below crest of model. The surcharge can also be seen (This is a negative).
All acceleration records are plotted from raw data.

FHL02. EQ 18
FHL02. EQ 14
FHL01. EQ 24
FHL01. EQ 17
FHL01. EQ 13
FHL01. EQ 8
FHL01. EQ 5

Scales:
Horizontal 1 cm : 10 msecs
Vertical 1 cm : 20 x
Figure 7  Transducer positions for test series FHLO1

Figure 8  Transducer positions for test series FHLO2
1024 data points per transducer, plotted after 1 smoothing pass

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Scales: model

TEST FHL01G
MODEL SED152, EQ5
FLIGHT 2

SHORT-TERM
TIME RECORDS

G = 40.2 g
Kin = 2.01%
Kout = 11.6%

FIG. NO. 9a
1024 data points per transducer, plotted after 1 smoothing pass

Scales : model

TEST FHL01B
MODEL SE0152
FLIGHT 2

LONG-TERM
TIME RECORDS

\[ G = 39.4 \, g \]
\[ \text{Kin} = 2.01\% \]
\[ \text{Kout} = 6.83\% \]

FIG. NO. 9b
1024 data points per transducer, plotted after 1 smoothing pass

Scales: model

TEST FHLO15
MODEL SE01S2
FLIGHT 2

SHORT-TERM
TIME RECORDS

G = 40.2g
Kin = 3.54%
Kout = 20.6%

FIG. NO.
10a

215
1024 data points per transducer, plotted after 1 smoothing pass

Scales: model

TEST FHL01B
MODEL SEC01S2
FLIGHT 2

LONG-TERM
TIME RECORDS

G = 39.4 g
Kin = 3.54 %
Kout = 15.1 %

Fig. No. 10b
1024 data points per transducer, plotted after 1 smoothing pass

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<td>-34.9 %</td>
<td>ACC258 50.0 %/cm</td>
<td></td>
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</tr>
<tr>
<td>71.4 %</td>
<td></td>
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</tr>
<tr>
<td>-33.9 %</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>33.3 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-30.2 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.1 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-30.4 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.3 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-32.0 %</td>
<td></td>
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Scales: model

<table>
<thead>
<tr>
<th>TEST FHL013</th>
<th>MODEL SE0152</th>
<th>EQ.13</th>
<th>SHORT-TERM TIME RECORDS</th>
<th>G = 40.2g</th>
<th>Kin = 6.95%</th>
<th>Kout = 32.7%</th>
<th>FIG. NO.</th>
</tr>
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<tbody>
<tr>
<td>FLIGHT 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11a</td>
</tr>
</tbody>
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217
1024 data points per transducer, plotted after 1 smoothing pass

Scales: model

TEST FHLO1B
MODEL SE0152
FLIGHT 3

LONG-TERM TIME RECORDS

$G = 39.4g$
$K_{in} = 6.95\%$
$K_{out} = 24.1\%$

FIG. NO. 

218
1024 data points per transducer, plotted after 1 smoothing pass

Scales: model

TEST FHL01C
MODEL 5E01S3
FLIGHT 4

G = 40.2g
Kin = 3.53%
Kout = 27.6%

FIG.NO. 12a
1024 data points per transducer, plotted after 1 smoothing pass

Scales: model

TEST FHLO1C
MODEL SE01S3
FLIGHT 4

LONG-TERM TIME RECORDS

G = 39.4g
Kin = 3.53%
Kout = 21.1%

FIG. NO. 12b
1024 data points per transducer, plotted after 1 smoothing pass

---

**Scales:**

- **TEST** FHL01C
- **MODEL** SE01S3
- **FLIGHT** 5
- **SHORT-TERM** TIME RECORDS

**G** = 40.2 g
**Kin** = 7.98%
**Kout** = 35.8%

**FIG. NO.** 13a
1024 data points per transducer, plotted after 1 smoothing pass.

Scales: model

TEST FHLO1C
MODEL SE0153
FLIGHT 5

LONG-TERM
TIME RECORDS

G = 39.4 g
Kin = 7.98 %
Kout = 25.8 %
1024 data points per transducer, plotted after 1 smoothing pass.

Scales: model

TEST FHLO2C
MODEL SE0293
FLIGHT 3
SHORT-TERM TIME RECORDS

G = 39.4g
Kin = 4.56%
Kout = 28.0%

FIG NO. 14a
1024 data points per transducer, plotted after 1 smoothing pass

Scales: model

<table>
<thead>
<tr>
<th>TEST FHLO2C</th>
<th>MODEL SE02S3</th>
<th>FLIGHT 3</th>
<th>EQ.14</th>
<th>LONG-TERM TIME RECORDS</th>
<th>$G = 39.4g$</th>
<th>$K_1 = 4.56%$</th>
<th>$K_{out} = 20.3%$</th>
<th>FIG. NO.</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>14 b</td>
</tr>
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</table>
1024 data points per transducer, plotted after 1 smoothing pass

Scales : model

<table>
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<tr>
<th>TEST FHLO2C</th>
<th>MODEL SE02S3</th>
<th>FLIGHT 3</th>
<th>EQ 18</th>
<th>SHORT-TERM</th>
<th>TIME RECORDS</th>
<th>G = 39.4 g</th>
<th>Kin = 7.07 %</th>
<th>Kout = 36.6 %</th>
<th>FIG. NO</th>
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<td>15a</td>
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</table>

225
1024 data points per transducer, plotted after 1 smoothing pass

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Time (milliseconds)</th>
<th>Transducer</th>
<th>Scale (kPa/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.32</td>
<td>0-1400</td>
<td>PPT68</td>
<td>10.0</td>
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<td>-4.89</td>
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<tr>
<td>40.0</td>
<td>0-1400</td>
<td>PPT2338</td>
<td>50.0</td>
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<tr>
<td>-14.7</td>
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<tr>
<td>8.61</td>
<td>0-1400</td>
<td>PPT2335</td>
<td>10.0</td>
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<tr>
<td>-3.13</td>
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<tr>
<td>20.3</td>
<td>0-1400</td>
<td>PPT2252</td>
<td>20.0</td>
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<tr>
<td>-5.96</td>
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<tr>
<td>16.1</td>
<td>0-1400</td>
<td>PPT2331</td>
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<td>-12.0</td>
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<tr>
<td>14.1</td>
<td>0-1400</td>
<td>PPT2330</td>
<td>20.0</td>
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<tr>
<td>-7.17</td>
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<tr>
<td>16.6</td>
<td>0-1400</td>
<td>PPT2333</td>
<td>20.0</td>
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<tr>
<td>26.3</td>
<td>0-1400</td>
<td>ACC1225</td>
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<td>%</td>
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</tbody>
</table>

Scales: model

Test FHL02C
Model SE02S3
Flight 3
time records

Long-term

G = 39.4 g
Kin = 7.07%
Kout = 25.6%

Figure No. 15b
Figure 16. a - 1. Kamaajou Figure for earthquake 5, tent PIHO1.
Figure 16 m - q
Figure 17 a - Lissajous Figures for earthquake 8, test FHL01.
Figure 17 m - q
Figure 18a Negative of blue sand grid before test FHL02.

Figure 18b Negative of blue sand grid after test FHL02.
3.1 Sinusoidal Waves (after Haag, 1962)

a. Wave on y-axis has a frequency twice that of wave on x-axis and lags the latter by a phase angle of $\beta$. For various values of $\beta$, the Lissajous figures are as shown in Fig. I.1 below.

![Figure I.1](after Haag, 1962)

b. Wave on y-axis has a frequency 1.5 times that of wave on x-axis and lags the latter by a phase angle of $\beta$. For various values of $\beta$, the Lissajous figures are as shown in Fig. I.2.

![Fig. I.2](after Haag, 1962)
3.2 Triangular Waves (after Dean, 1981)

Figure L3 Lissajous Figures for Triangular Waves (after Dean, 1981)
3.3 Square Waves and Triangular Waves (after Dean, 1981)

Square and Triangular 'in phase'

Square lags Triangular by 45°

Square lags Triangular by 90°

Square lags Triangular by 135°

Figure 1.4 Square Wave Lagging Triangular Wave (after Dean, 1981).

Calculation of Phase Lag