

**Use of inclined micro-piles as a
liquefaction remediation method for
existing buildings – Data report on
centrifuge tests MP1, MP2 and MP3**

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1. Introduction

This report describes three centrifuge tests carried out as part of the NEMISREF project, at 50g, to investigate the behaviour of inclined, non-load-bearing micro-piles as a liquefaction remediation measure for existing buildings. The complete results from these three tests are presented. In order to assess the effectiveness of the arrangement of micro-piles tested as a liquefaction remediation method, the results can be compared with those from centrifuge tests on similar unimproved soil profiles. These results can be found in technical report CUED/D-SOILS/TR.342 and full analysis, comparison and discussion of the results is given in Mitrani 2006, PhD thesis, University of Cambridge.

2. Description of centrifuge models

Two model structures were used in these centrifuge tests: a single-degree-of-freedom (SDOF) structure and a two-degree-of-freedom (2DOF) structure. The SDOF structure had a natural frequency of 1.52Hz (prototype, 76Hz *model scale*) and a bearing pressure of 58kPa, while the 2DOF structure had a bearing pressure of 38kPa. Unfortunately, clear natural frequencies could not be obtained for this structure, perhaps due to inferior construction. The structures are shown in figures 1 and 2 at prototype scale.

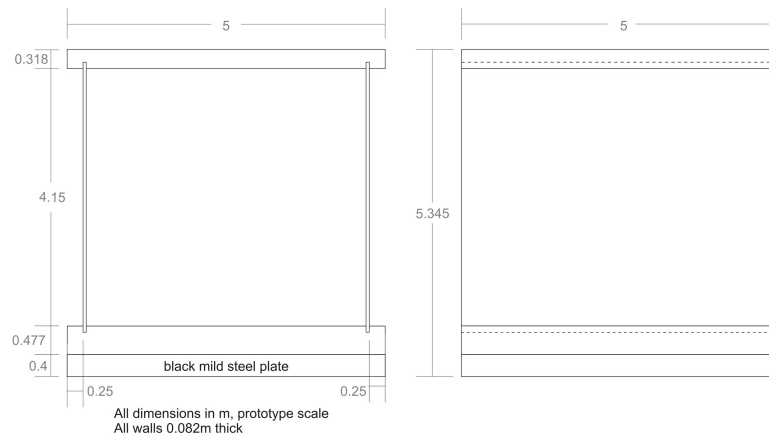


Figure 1: Diagram of SDOF structure

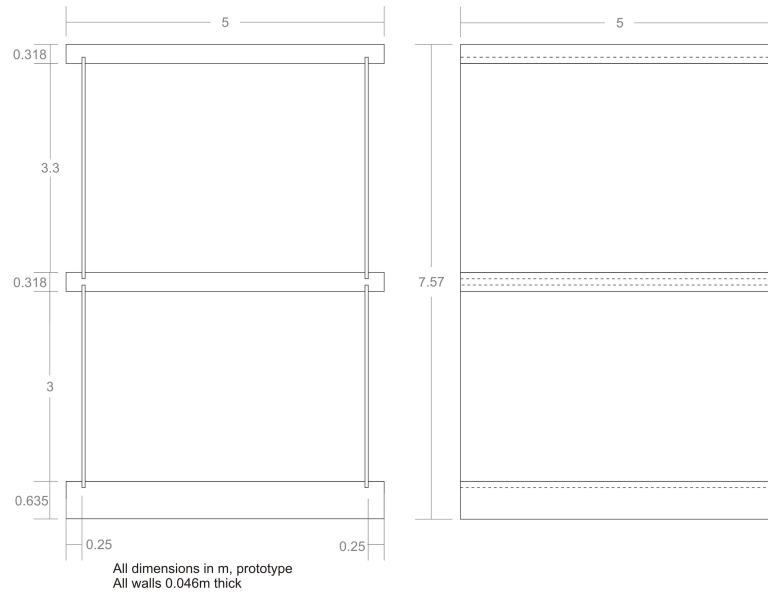


Figure 2: Diagram of 2DOF structure

Centrifuge test MP1 was carried out on a model consisting of the SDOF structure founded on a deep (15.75m, 315mm) homogeneous bed of liquefiable sand. Two layers of micro-piles, inclined at 45° were inserted under the structure. In the lower layer, the micro-piles extended to a depth of 8.75m (175mm) and were aligned longitudinally. The upper layer of micro-piles were aligned both longitudinally and transversely and extended to a depth of 5m (100mm). The transverse micro-piles in this layer had to be placed at around 60° due to space restrictions in the ESB box. The longer micro-piles were modelled using commercially bought knitting needles and the shorter ones with crochet hooks. All the micro-piles had a diameter of 0.275m (5.5mm) and were spaced at 1.25m (25mm) centre to centre. As the needles used to model the micro-piles were smooth, they were roughened by gluing sand to them. It was hoped that this would improve the interface friction between the needles and the sand. All the micro-piles were anchored at the sand surface with blocks of plaster of Paris. Photographs of the upper and lower layers of micro-piles can be seen in figures 3 and 4 respectively. The instrument layout for the model used in centrifuge test MP1 is shown in figure 5, at prototype scale.

Centrifuge test MP2 was similar to MP1, except the 2DOF structure was used. The instrument layout for the model used in this centrifuge test is shown in figure 6, at prototype scale.



Figure 3: Photograph of arrangement of upper layer of micro-piles



Figure 4: Photograph of arrangement of lower layer of micro-piles

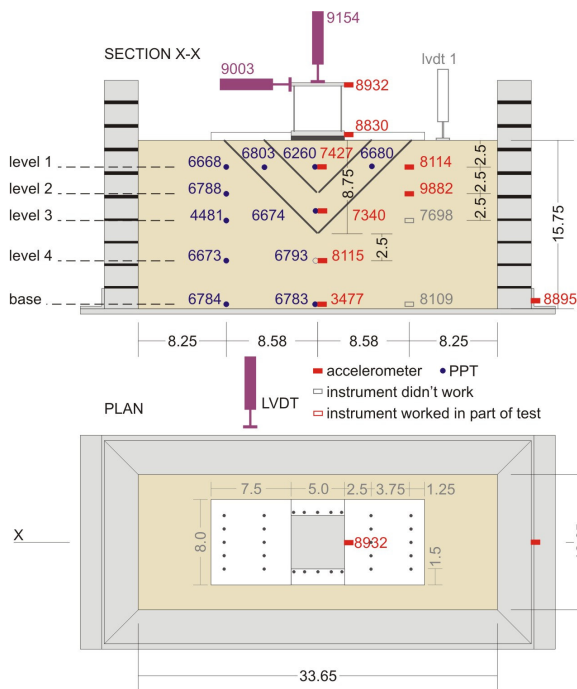


Figure 5: Instrument layout for centrifuge test MP1

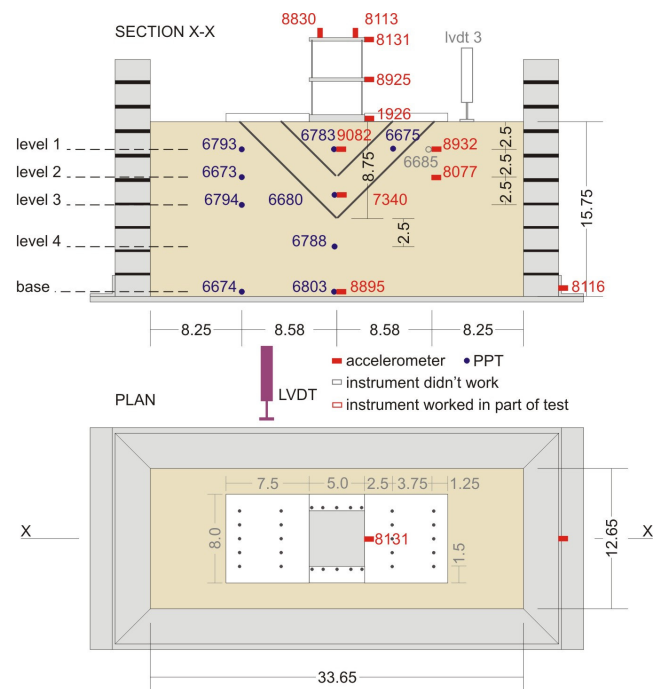


Figure 6: Instrument layout for centrifuge test MP2

Centrifuge test MP3 was carried out on a model with a layered sand profile. This profile consisted of a loose layer of liquefiable sand 7m (140mm) deep, overlying a dense layer of the same sand, 5m (100mm) deep. The same arrangement of micro-piles was adopted as for centrifuge tests MP1 and MP2 and these extended through the full depth of the liquefiable layer, into the

dense layer below. The instrument layout for centrifuge test WA3 is shown in figure 7, at prototype scale.

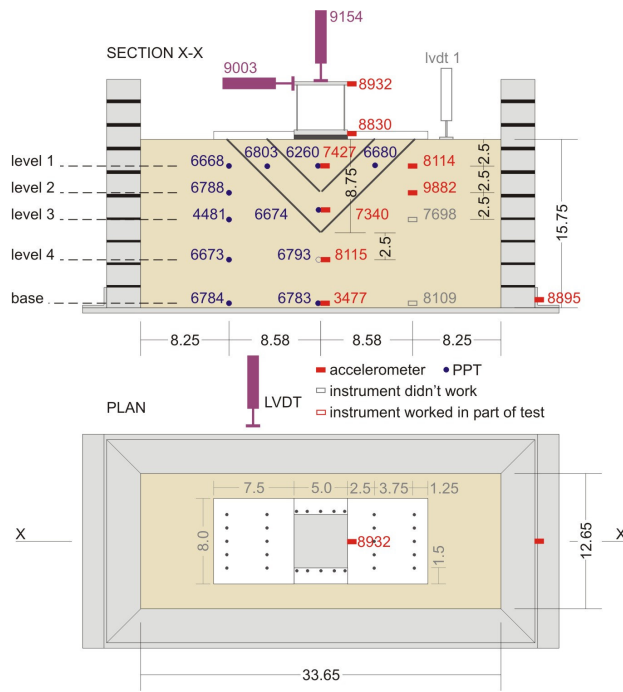


Figure 7: Instrument layout for centrifuge test MP3

3. Model Preparation

Each model was prepared in essentially the same way. Hostun S28 sand was air pluviated from an over-head hopper into the deep ESB box. A large orifice was used to produce the loose layers and the automatic sand pourer at the Schofield Centre was used to pour the dense layer in centrifuge test MP3. Before insertion of the micro-piles, moulds for the plaster blocks were constructed out of tin-foil and placed on the sand surface. The micro-piles were pushed through the tin-foil into the sand, along a guide to produce the correct inclination. After all the micro-piles were inserted into the sand, the holes in the tin-foil around them were sealed with silicon seal and the plaster blocks were poured. Saturation took place after the plaster had fully hardened. Each model was saturated under vacuum from the base, using 50cS methylcellulose. The structure was placed on the sand surface after each model was loaded onto the centrifuge to minimise structural settlement before testing. Full details of the preparation method for each and the materials and equipment used can be found in Mitrani 2006.

It should be noted that the dimensions and instrument positions shown in figures 5 to 7 represent the geometry that was aimed for during construction of the models. However, due to the difficulties of making precise models by hand, the actual prototype dimensions were often different. The actual properties of the sand layers in centrifuge tests MP1, MP2 and MP3 at prototype scale are shown in table 1.

Table 1: Properties of sand layers in models for centrifuge tests WA1P, WA1F and WA3

	MP1	MP2	MP3	
			loose	dense
layer thickness (m)	14.5	17.4	6.65	4.9
γ_{drv} (kN/m ³)	15.0	14.4	14.3	16.0
γ_{sat} (kN/m ³)	19.1	18.8	18.7	19.8
D_r (%)	60	44	42	85

4. Centrifuge Test Procedure

All three centrifuge tests were carried out at 50g. Five earthquakes were fired in centrifuge tests MP1 and MP3 but only four in centrifuge test MP2. The earthquakes were of difference size and frequency to investigate the behaviour of the structure thoroughly. The main details of the earthquakes fired in each test are shown in table 2, at prototype scale. The earthquakes were fired in order of increasing magnitude and frequency to try and minimise the effects of firing multiple earthquakes on a single model. Further details can be found in Mitrani 2006. It should be noted that in centrifuge test MP2 no frequency sweep earthquake was fired and in centrifuge test MP3, the order of earthquake 4 and the frequency sweep earthquake was reversed.

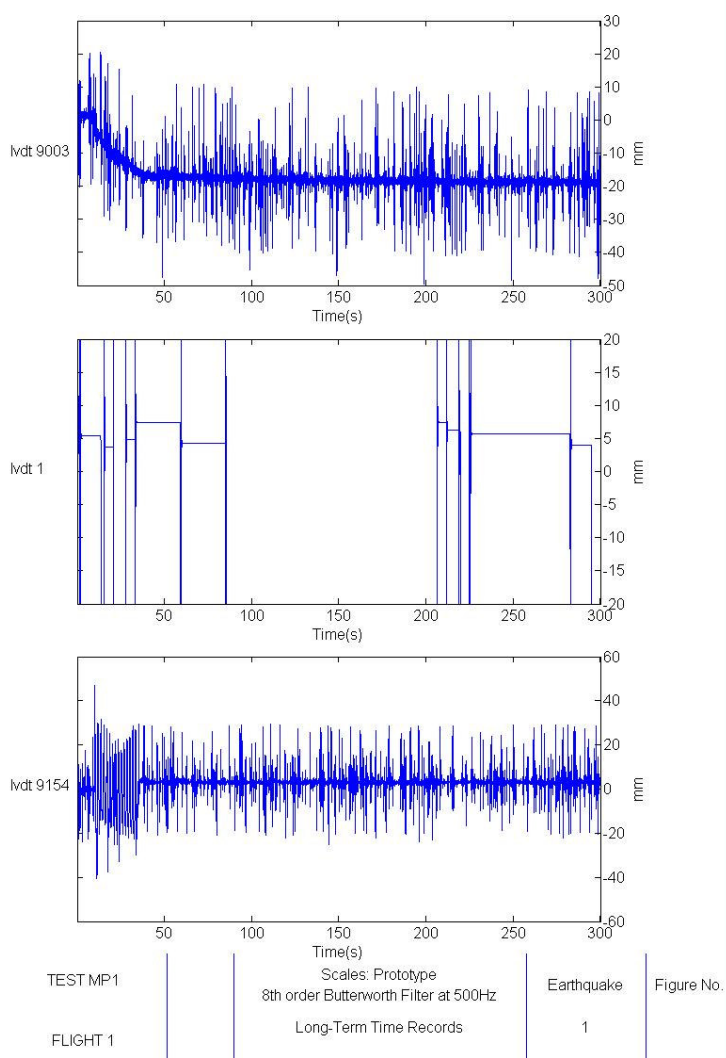
Table 2: Details of earthquakes fired in centrifuge tests WA1P, WA1F and WA3

	frequency (Hz)	duration (s)			max. base acc. (g)			no. of cycles		
		MP1	MP2	MP3	MP1	MP2	MP3	MP1	MP2	MP3
EQ1	0.6	27.5	27	27	0.07	0.05	0.07	17	17	17
EQ2	0.8	29	27	27	0.13	0.09	0.13	23	23	21
EQ3	1	29	27	27	0.18	0.11	0.2	28	27	27
sweep	1→0	≈179	-	≈183	0.22	-	0.26	≈106	-	≈112
EQ4	1	31	27	27	0.25	0.15	0.29	30	29	27

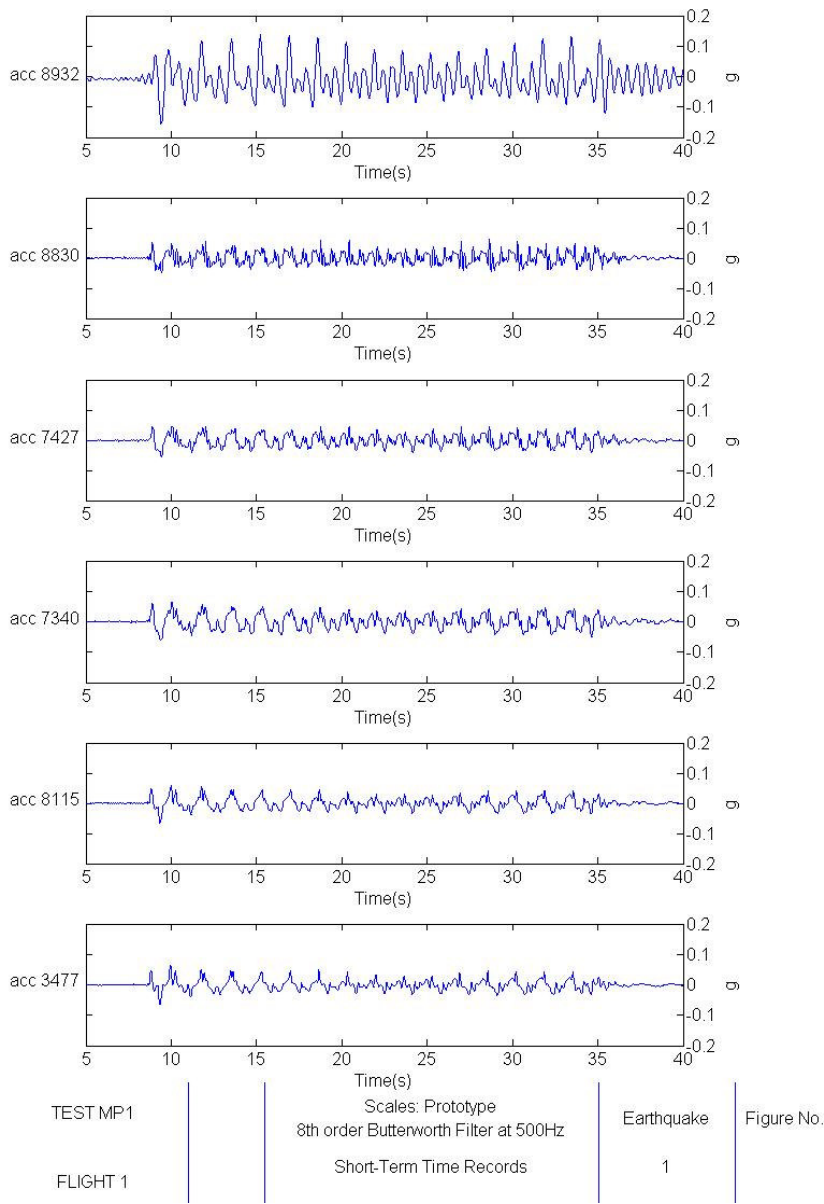
5. Results

5.1 Centrifuge test MP1, earthquake 1

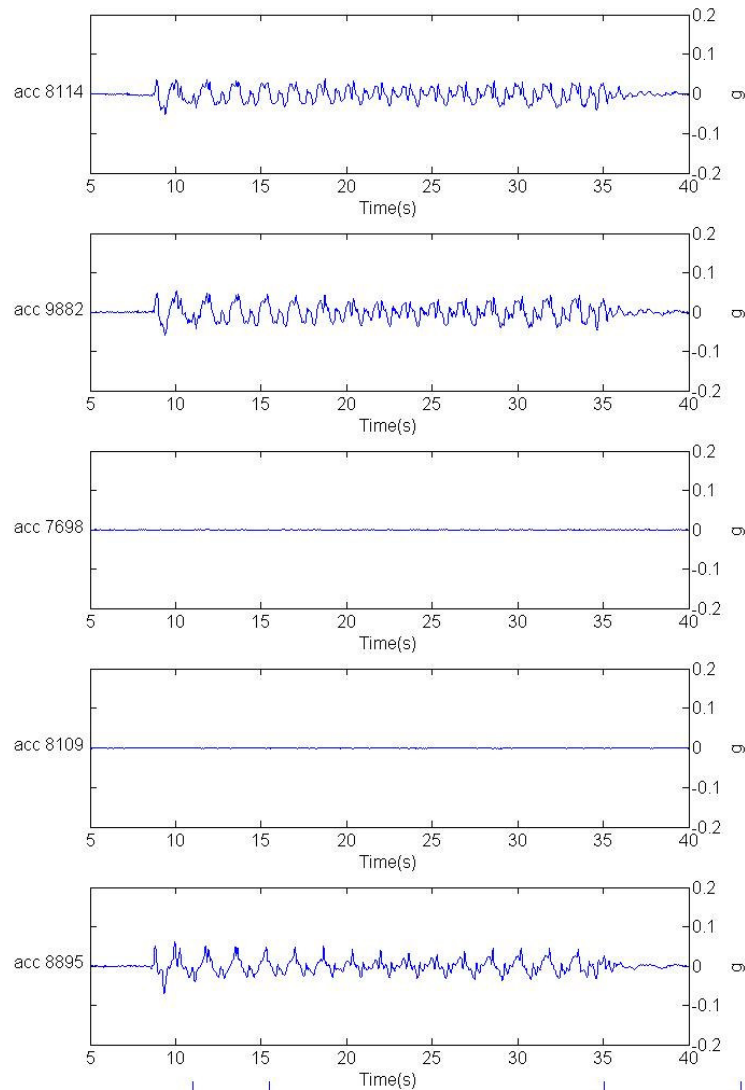
Soil and structural displacements



Accelerations of structure and soil under structure base



Accelerations away from structure and box (input) acceleration



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

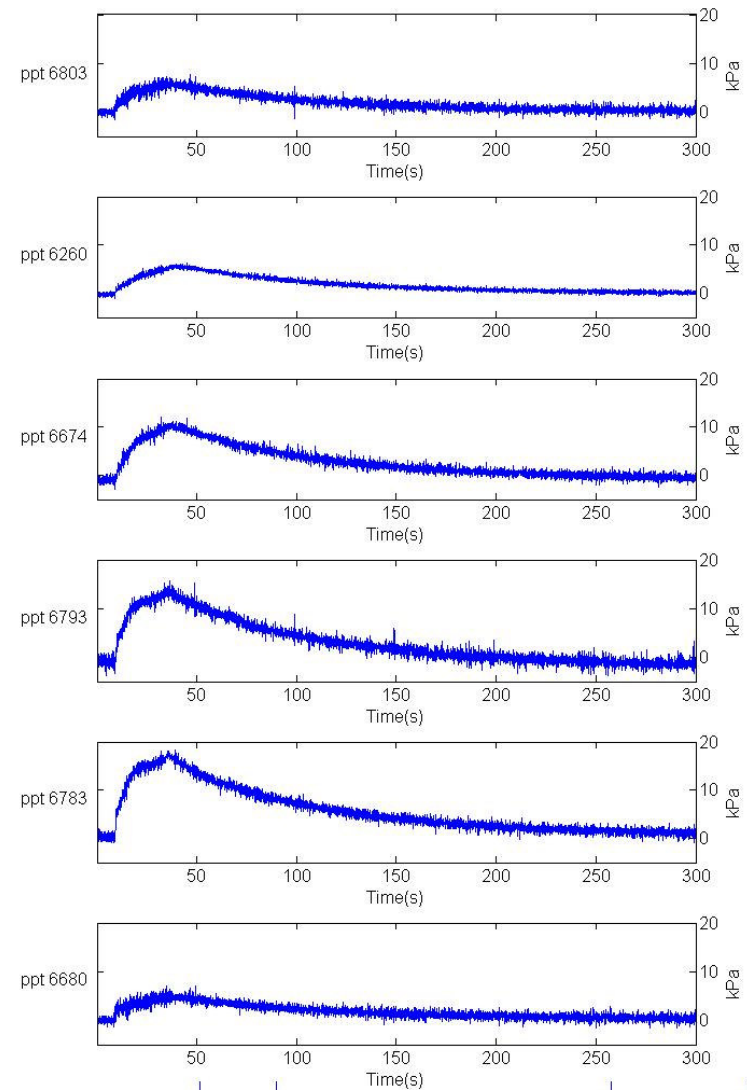
Figure No.

FLIGHT 1

Short-Term Time Records

1

Excess pore pressures under structure and between micro-piles



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

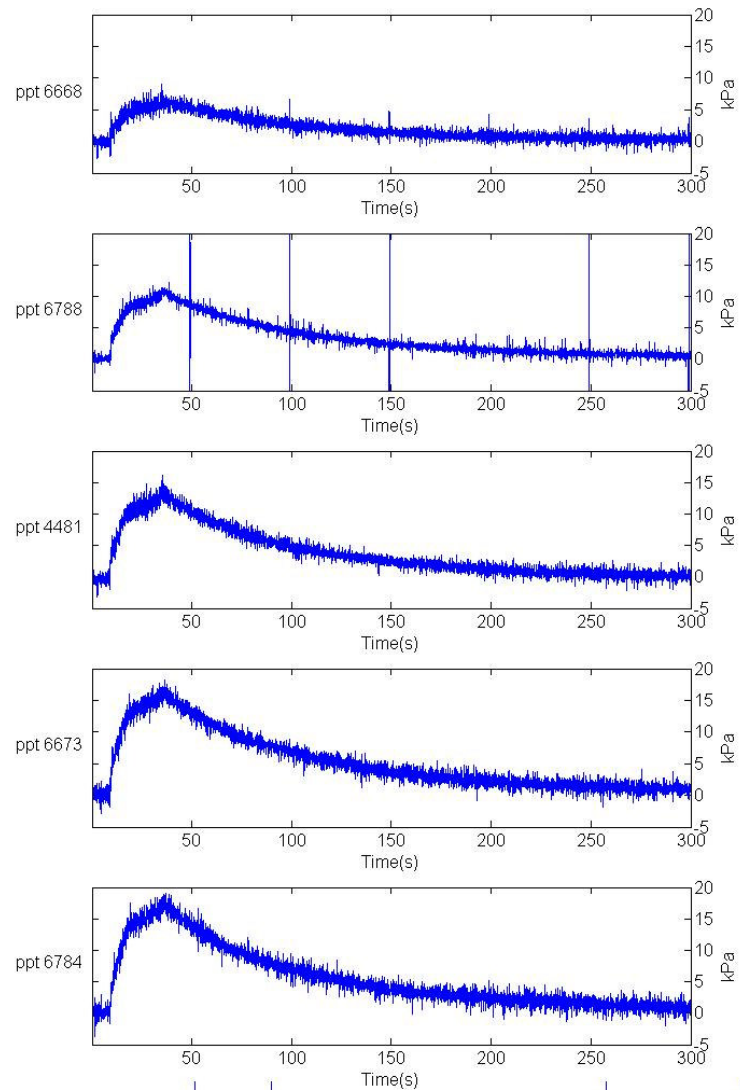
Figure No.

FLIGHT 1

Long-Term Time Records

1

Excess pore pressures away from structure



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

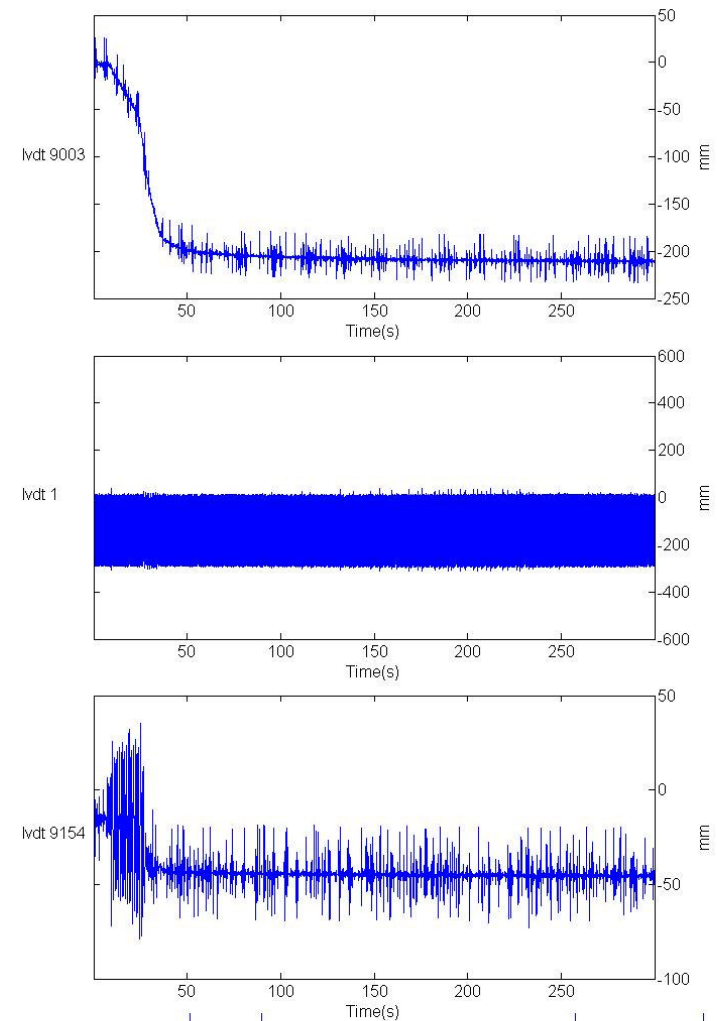
FLIGHT 1

Long-Term Time Records

1

5.2 Centrifuge test MP1, earthquake 2

Soil and structural displacements



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

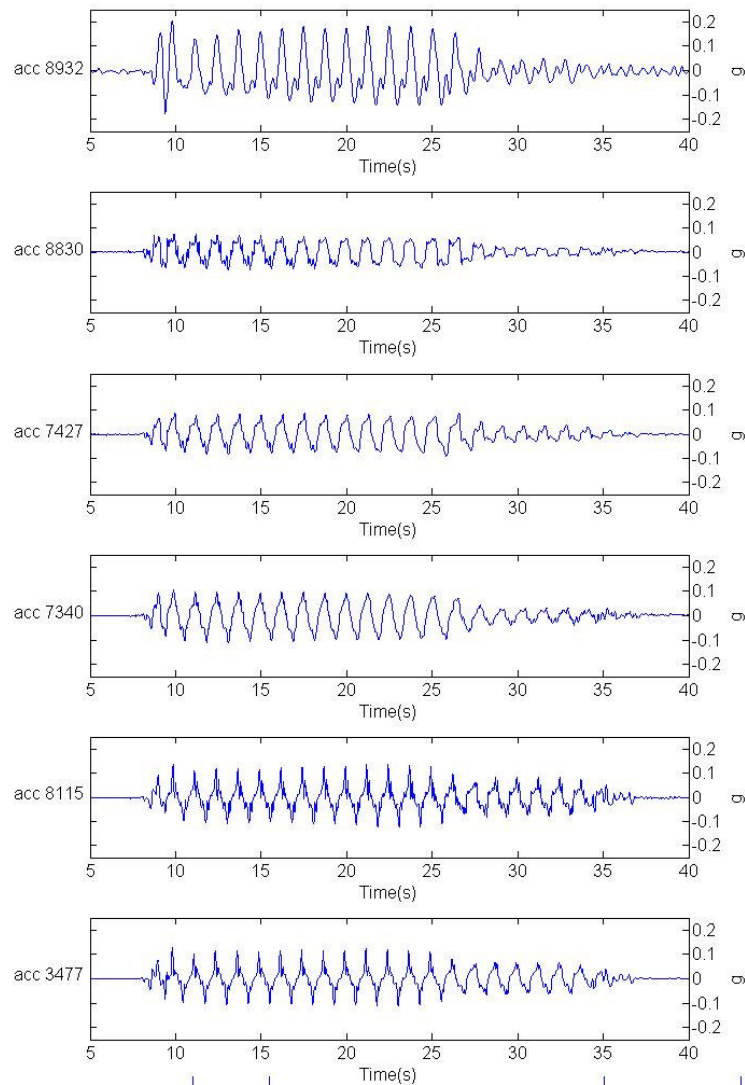
Figure No.

FLIGHT 1

Long-Term Time Records

2

Accelerations of structure and soil under structure base



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

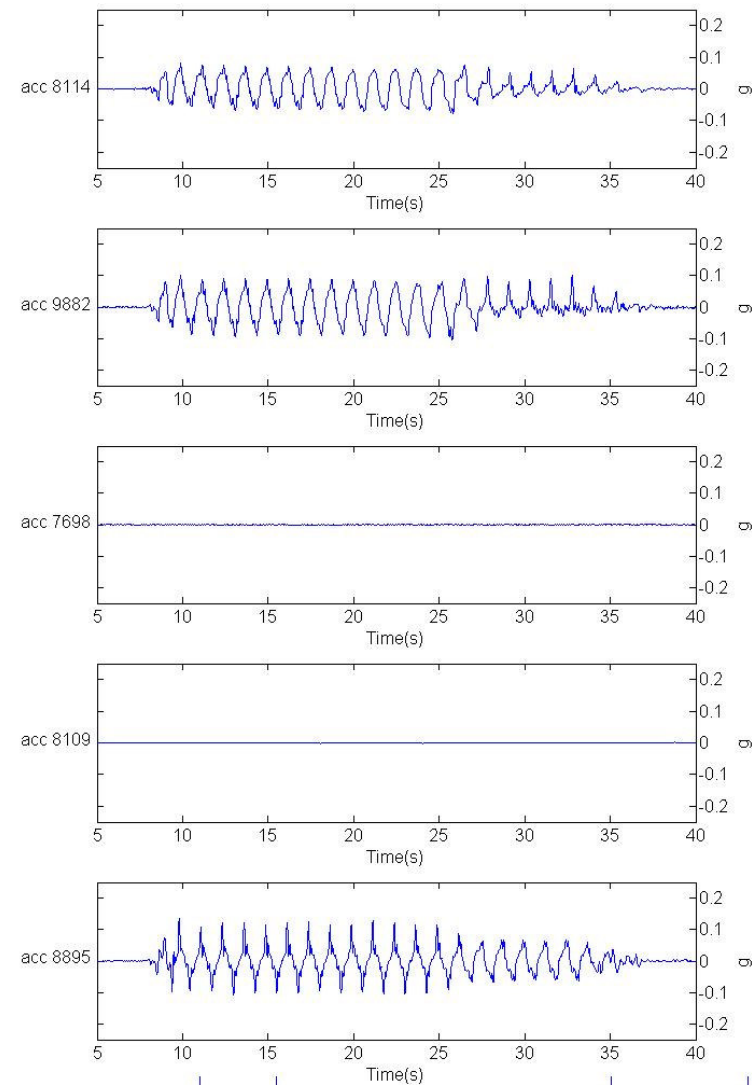
Figure No.

FLIGHT 1

Short-Term Time Records

2

Accelerations away from structure and box (input) acceleration



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

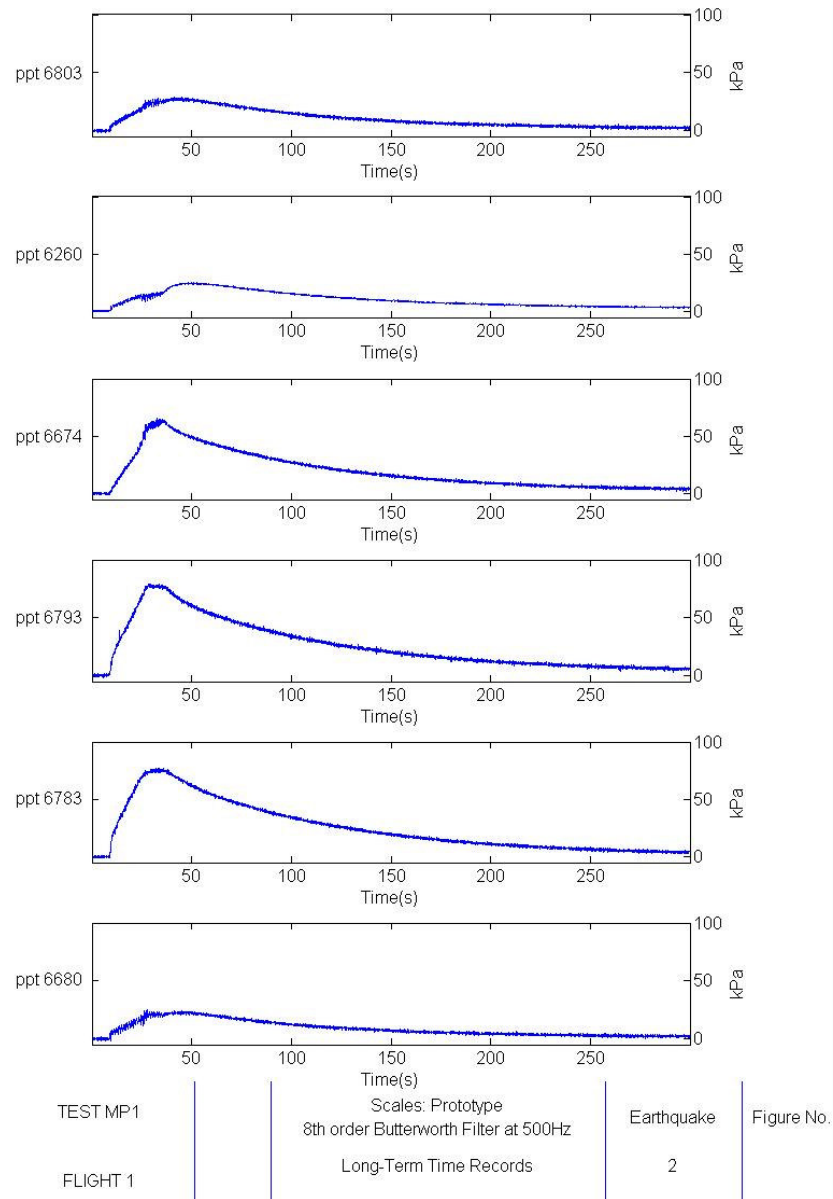
Figure No.

FLIGHT 1

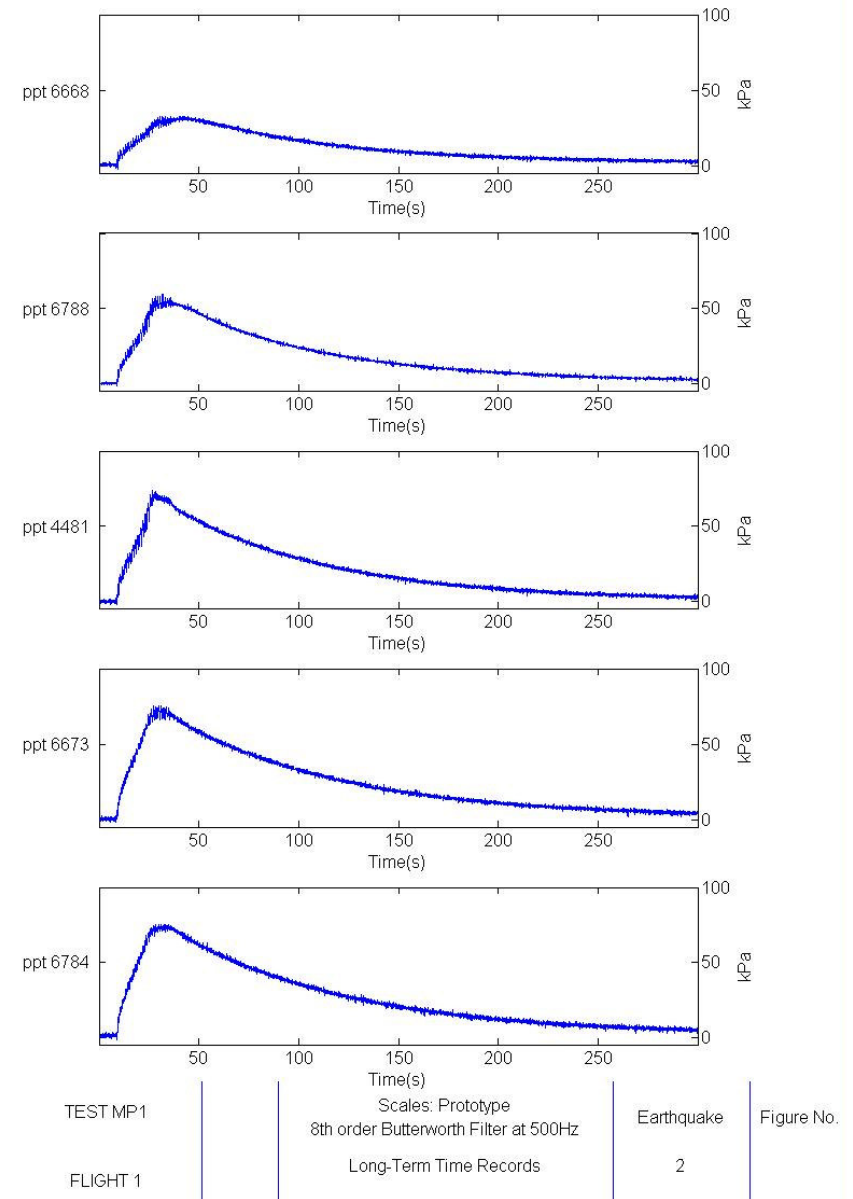
Short-Term Time Records

2

Excess pore pressures under structure and between micro-piles

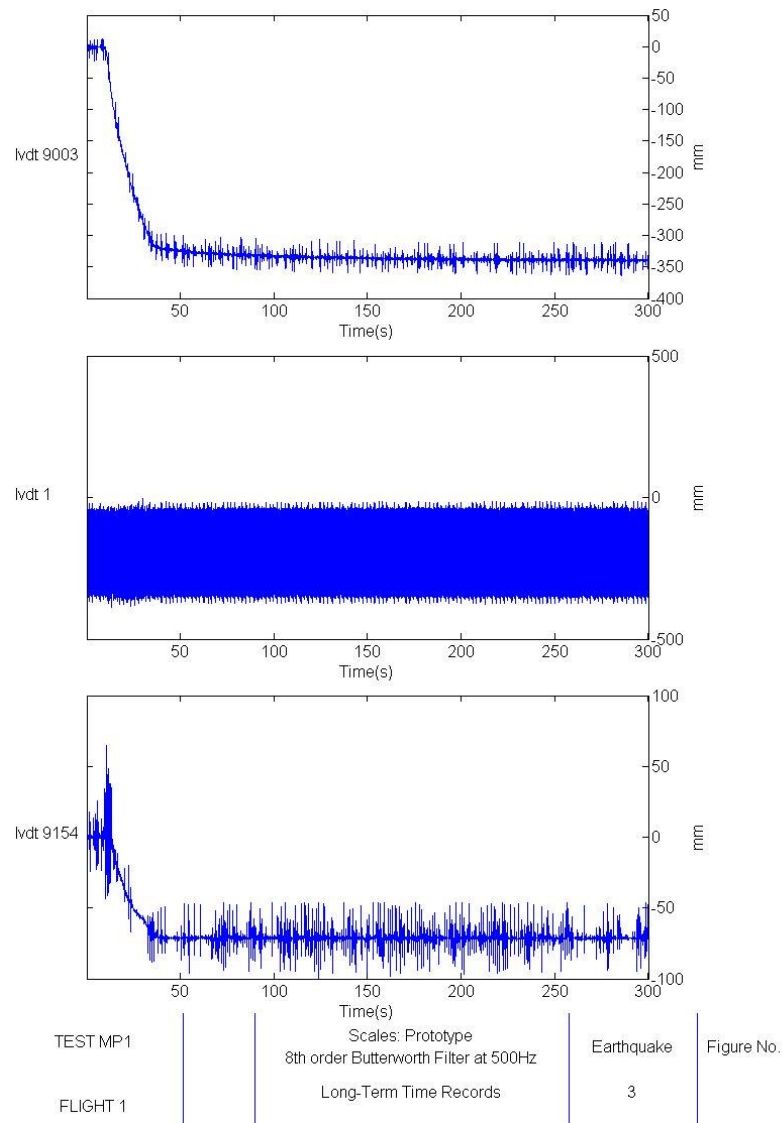


Excess pore pressures away from structure

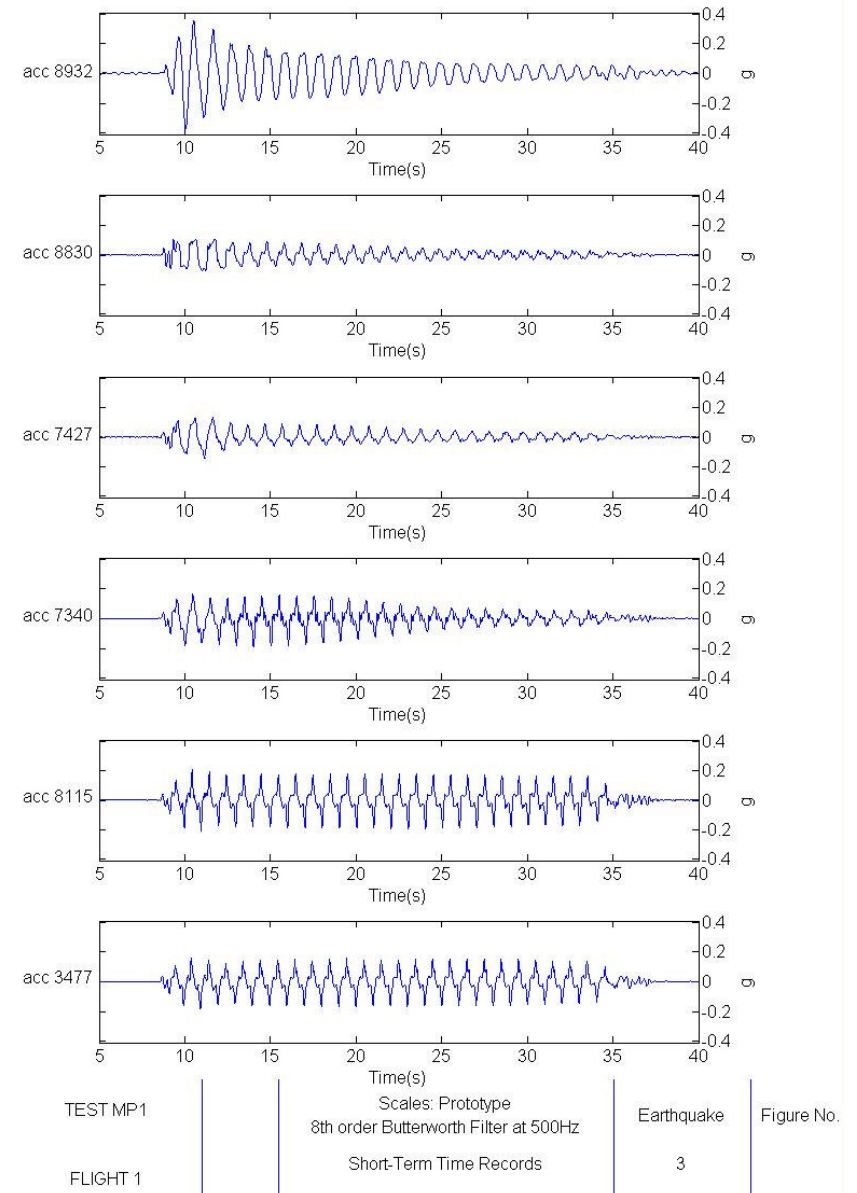


5.3 Centrifuge test MP1, earthquake 3

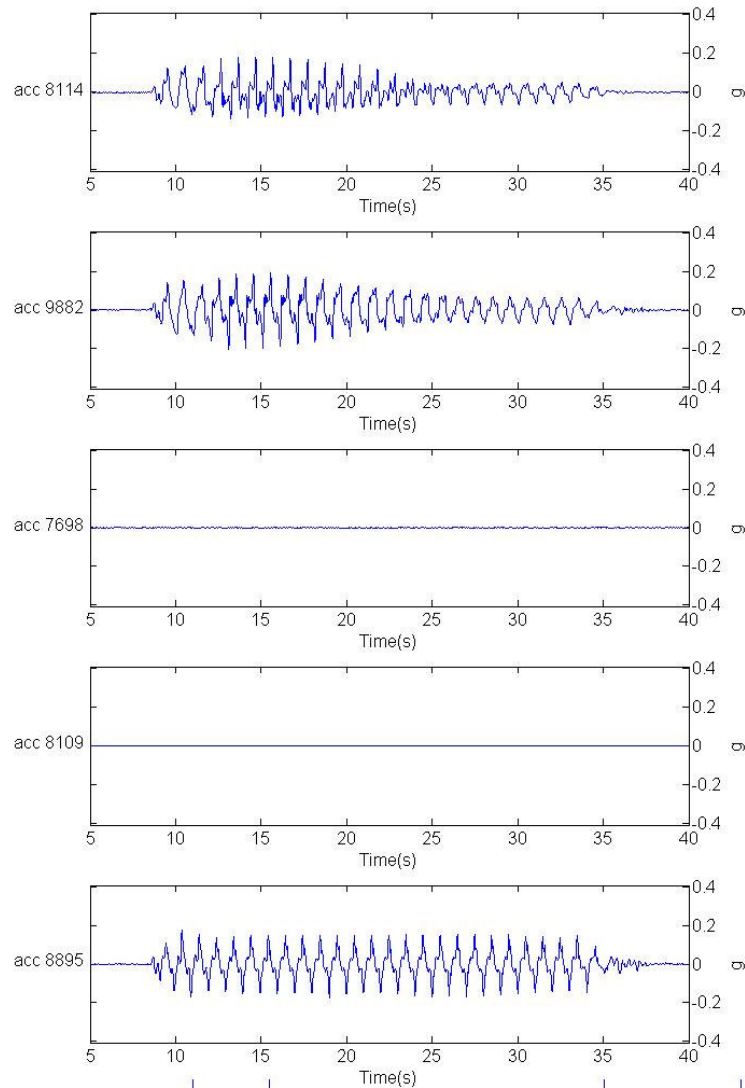
Soil and structural displacements



Accelerations of structure and soil under structure base



Accelerations away from structure and box (input) acceleration



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

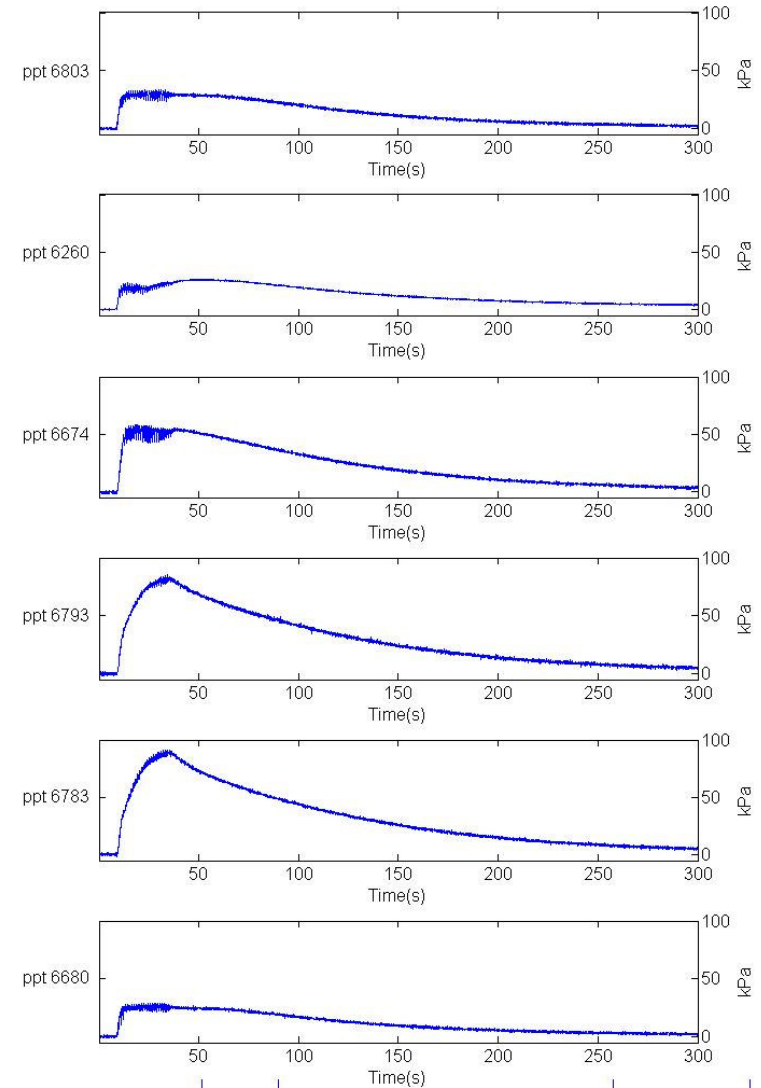
Figure No.

FLIGHT 1

Short-Term Time Records

3

Excess pore pressures under structure and between micro-piles



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

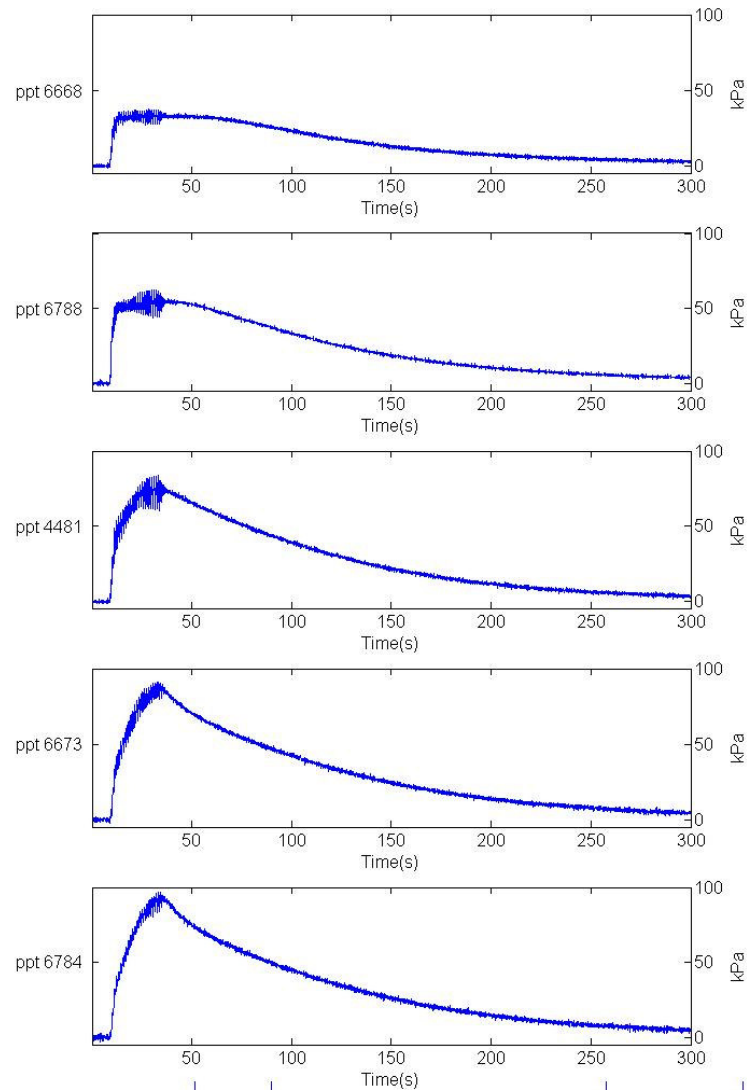
Figure No.

FLIGHT 1

Long-Term Time Records

3

Excess pore pressures away from structure



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

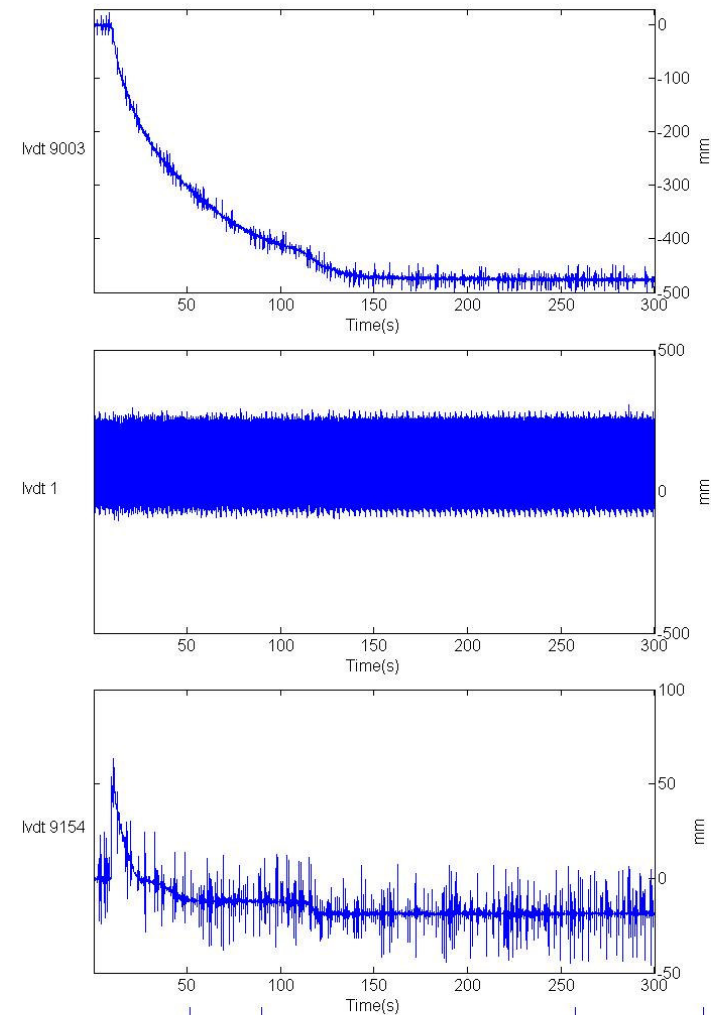
FLIGHT 1

Long-Term Time Records

3

5.4 Centrifuge test MP1, frequency sweep earthquake

Soil and structural displacements



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

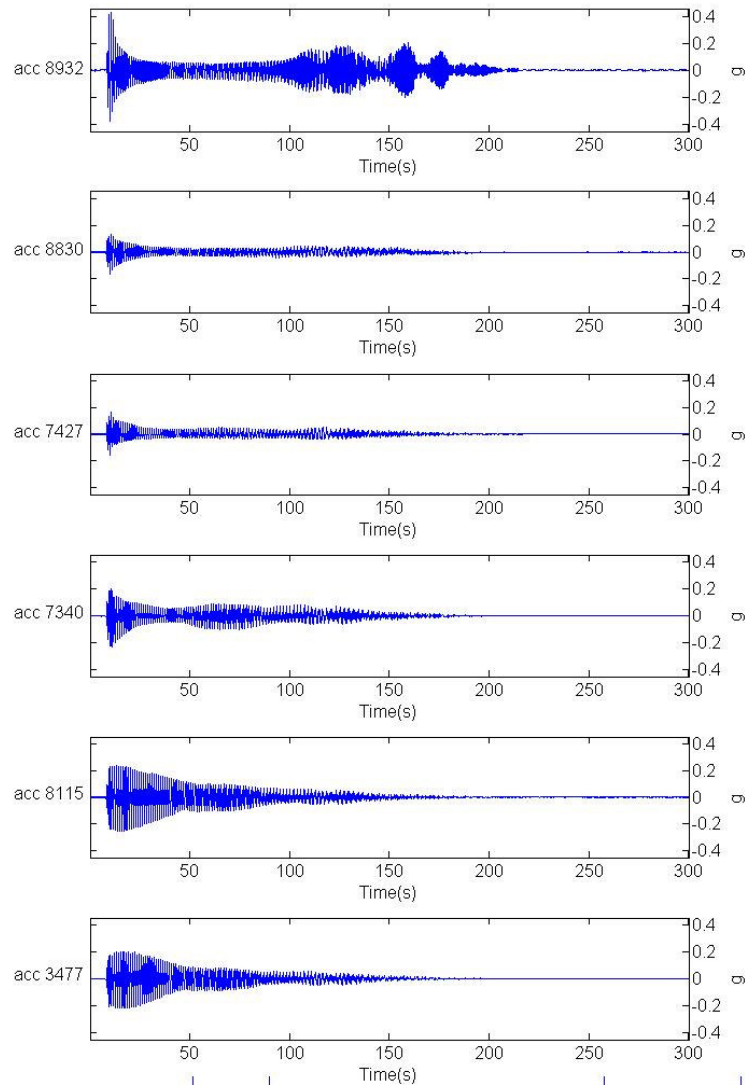
Figure No.

FLIGHT 1

Long-Term Time Records

sweep

Accelerations of structure and soil under structure base



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

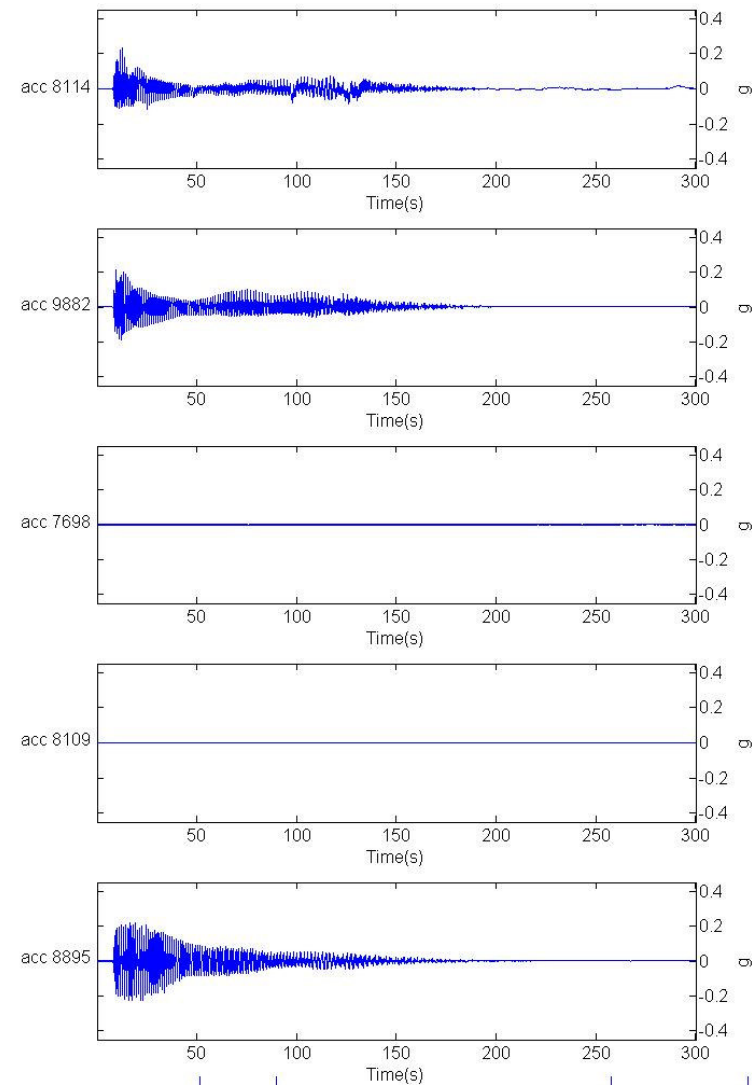
Figure No.

FLIGHT 1

Long-Term Time Records

sweep

Accelerations away from structure and box (input) acceleration



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

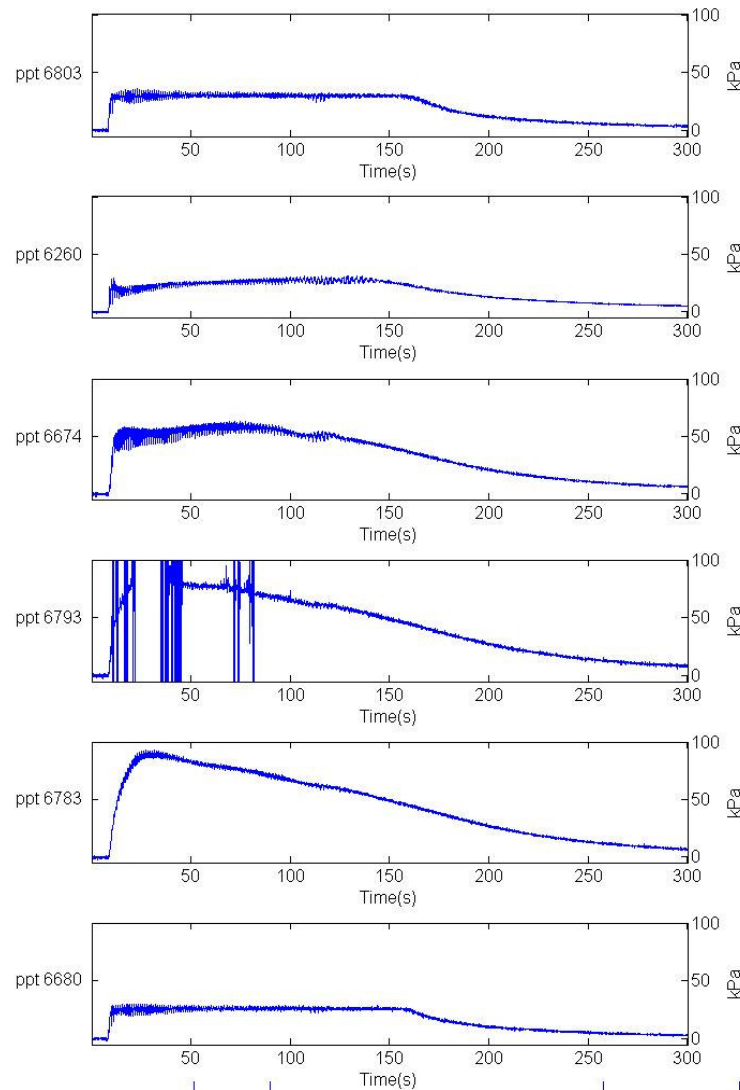
Figure No.

FLIGHT 1

Long-Term Time Records

sweep

Excess pore pressures under structure and between micro-piles



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

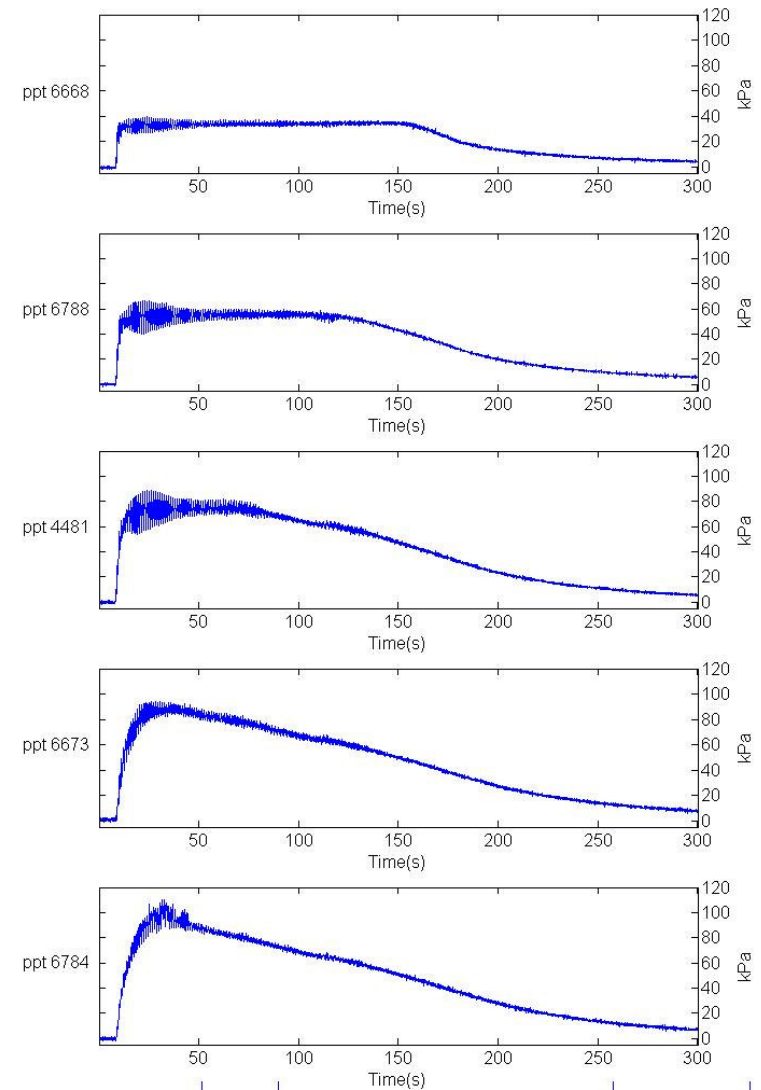
Figure No.

FLIGHT 1

Long-Term Time Records

sweep

Excess pore pressures away from structure



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

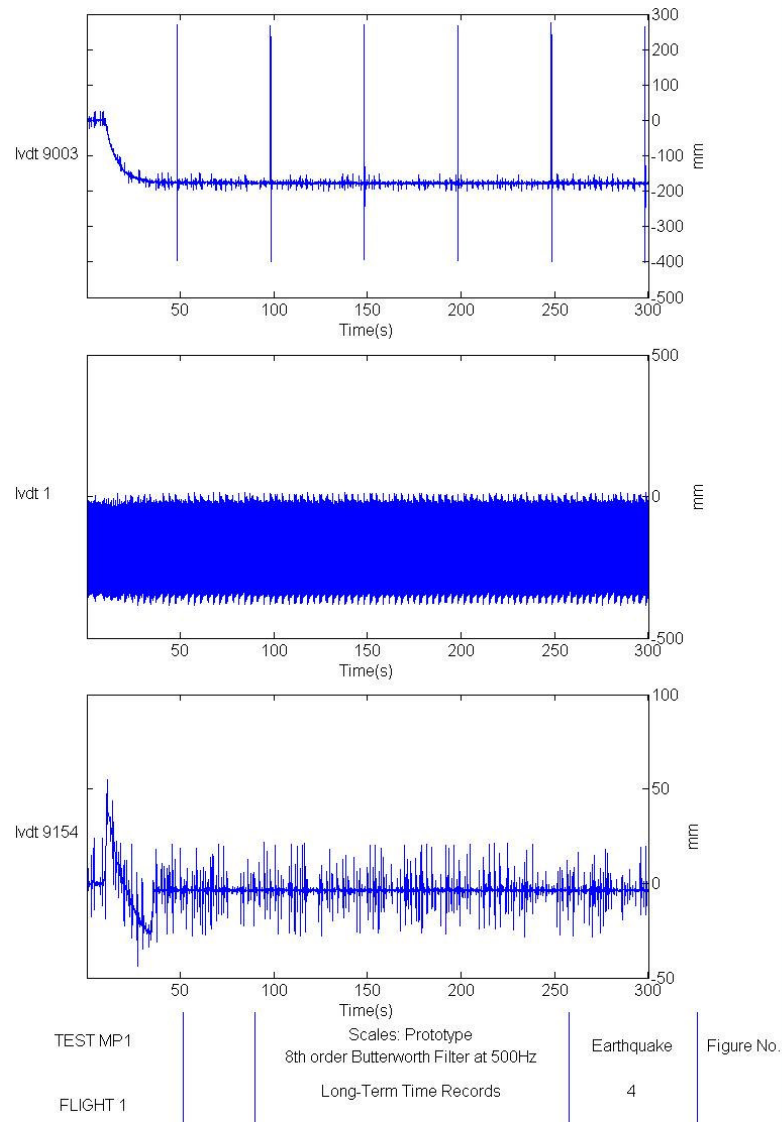
FLIGHT 1

Long-Term Time Records

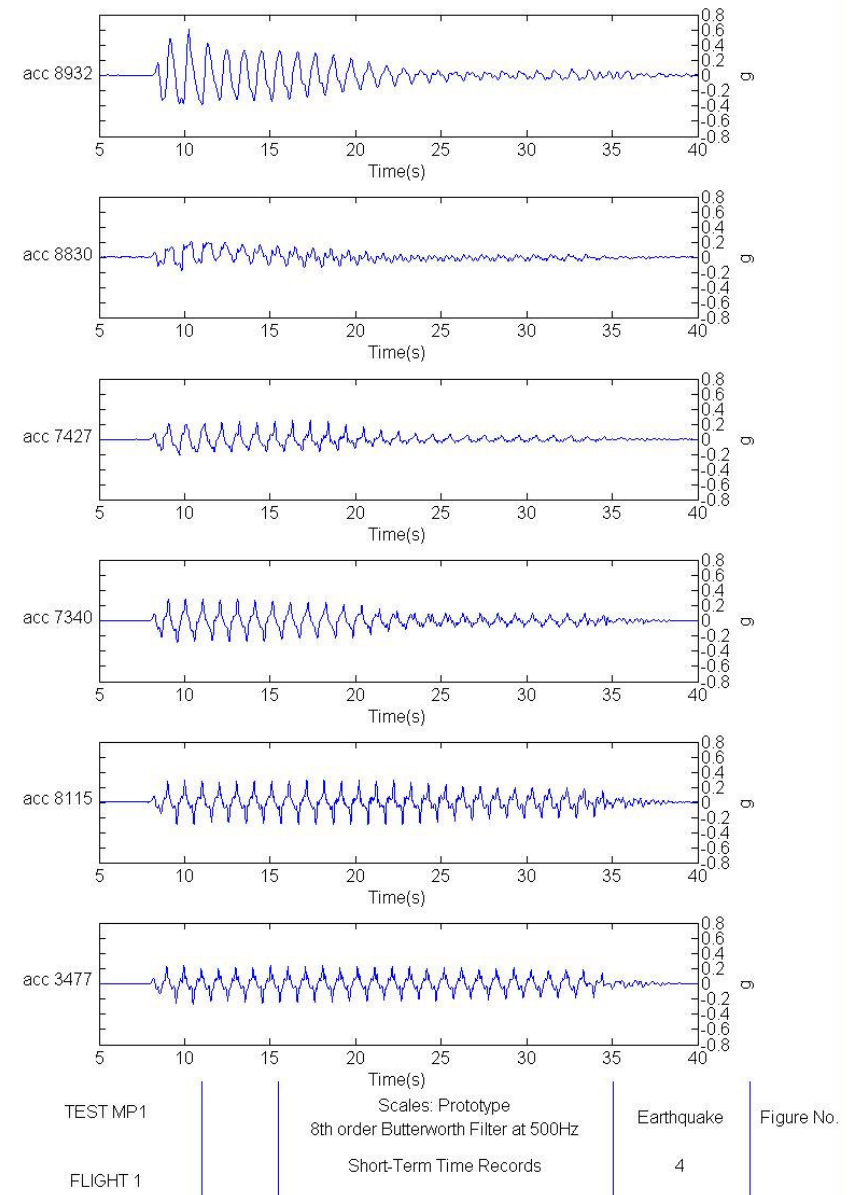
sweep

5.5 Centrifuge test MP1, earthquake 4

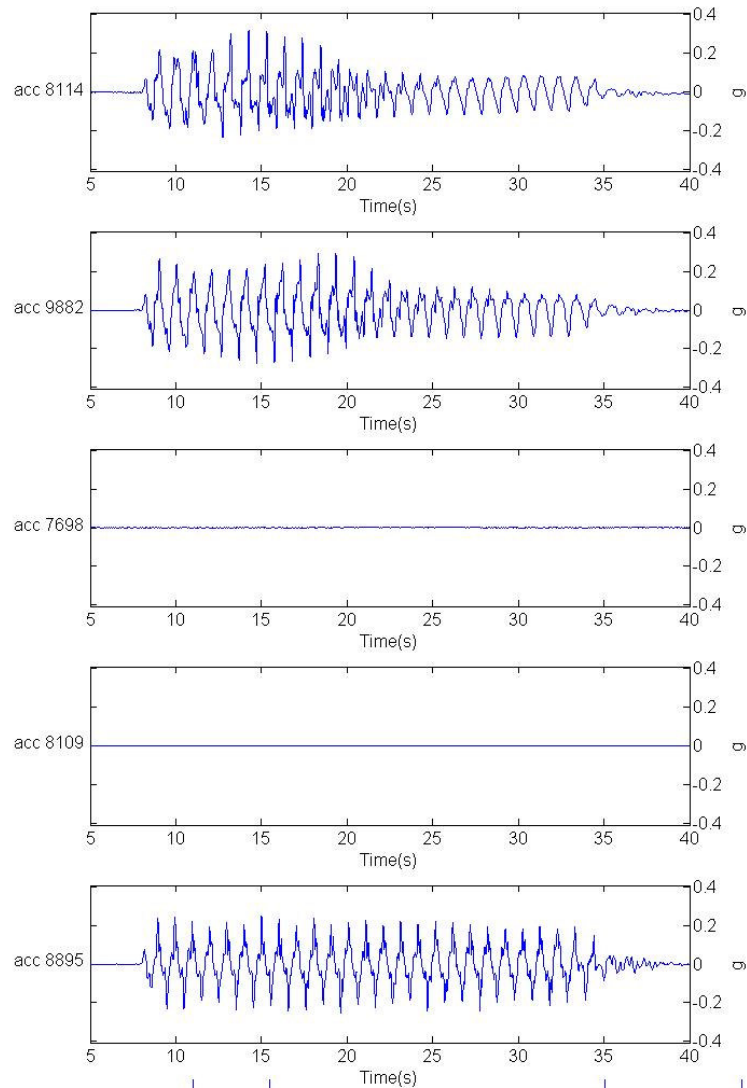
Soil and structural displacements



Accelerations of structure and soil under structure base



Accelerations away from structure and box (input) acceleration



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

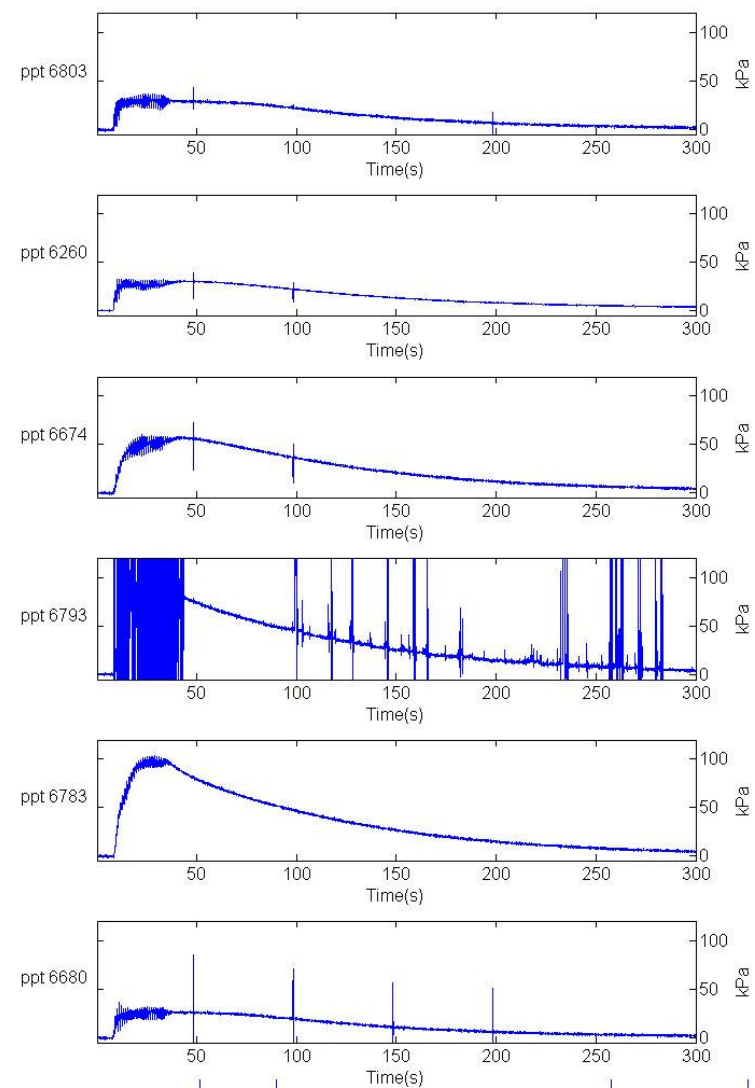
Figure No.

FLIGHT 1

Short-Term Time Records

4

Excess pore pressures under structure and between micro-piles



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

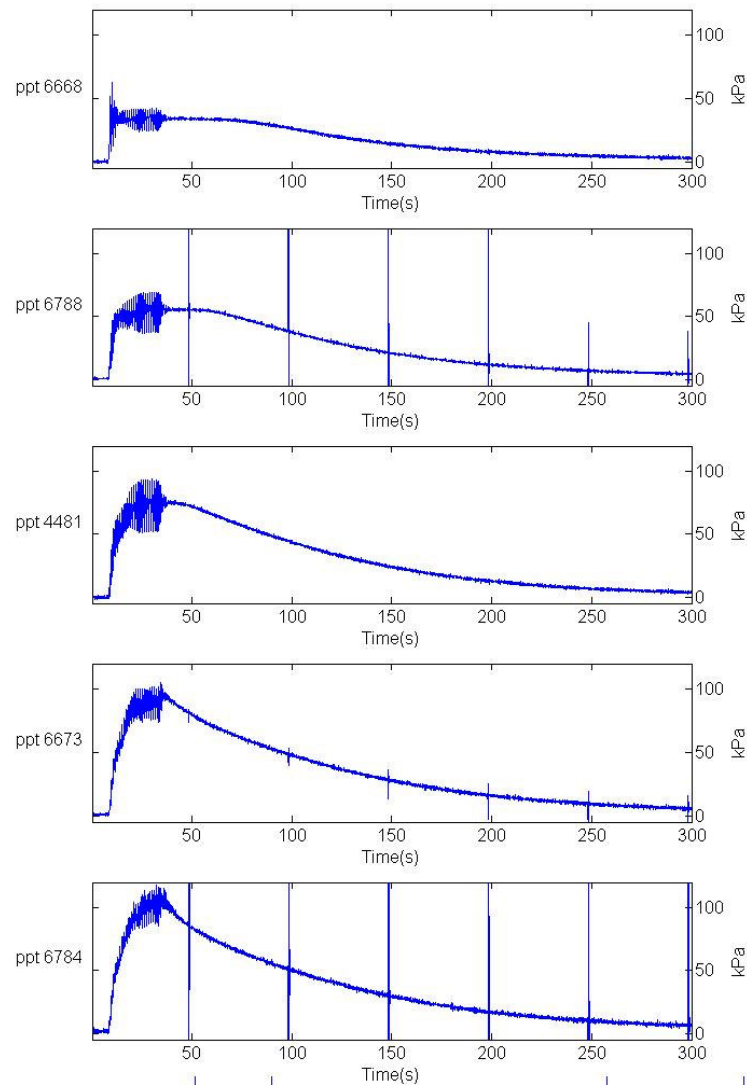
Figure No.

FLIGHT 1

Long-Term Time Records

4

Excess pore pressures away from structure



TEST MP1

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

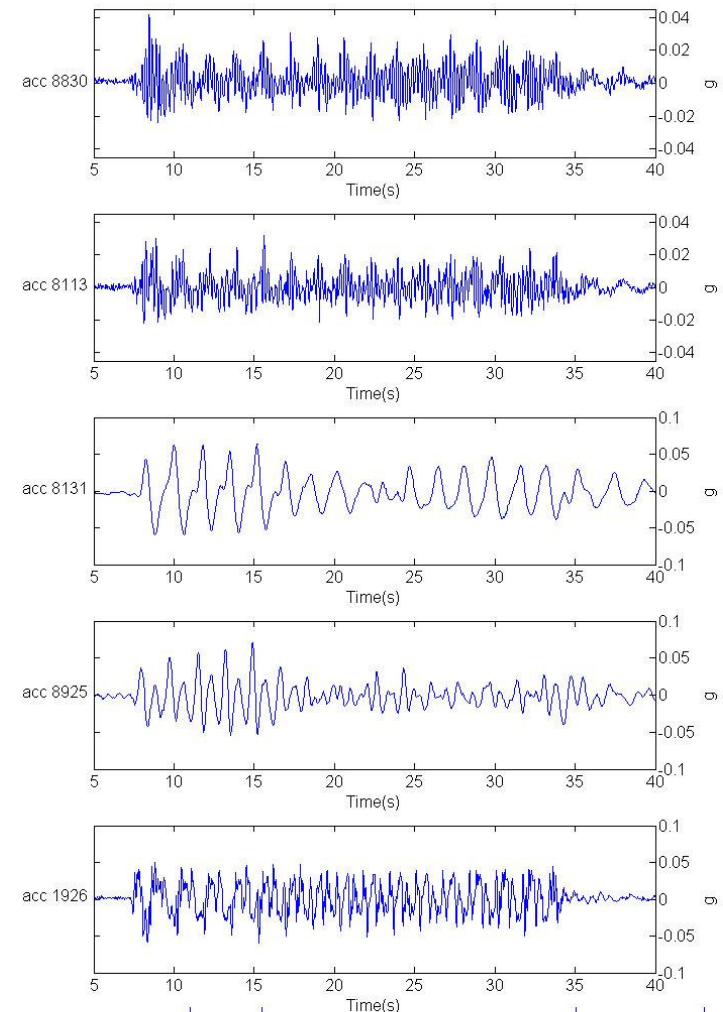
FLIGHT 1

Long-Term Time Records

4

5.6 Centrifuge test MP2, earthquake 1

Vertical and horizontal structural accelerations



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

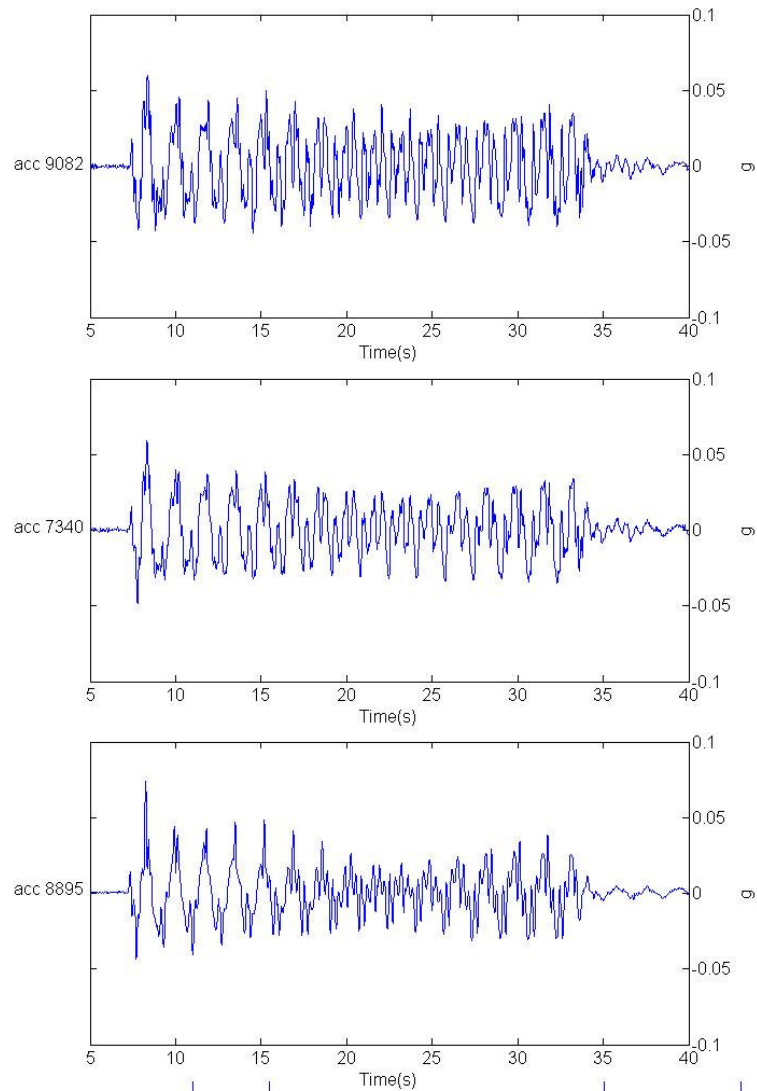
Figure No.

FLIGHT 1

Short-Term Time Records

1

Accelerations under structure



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

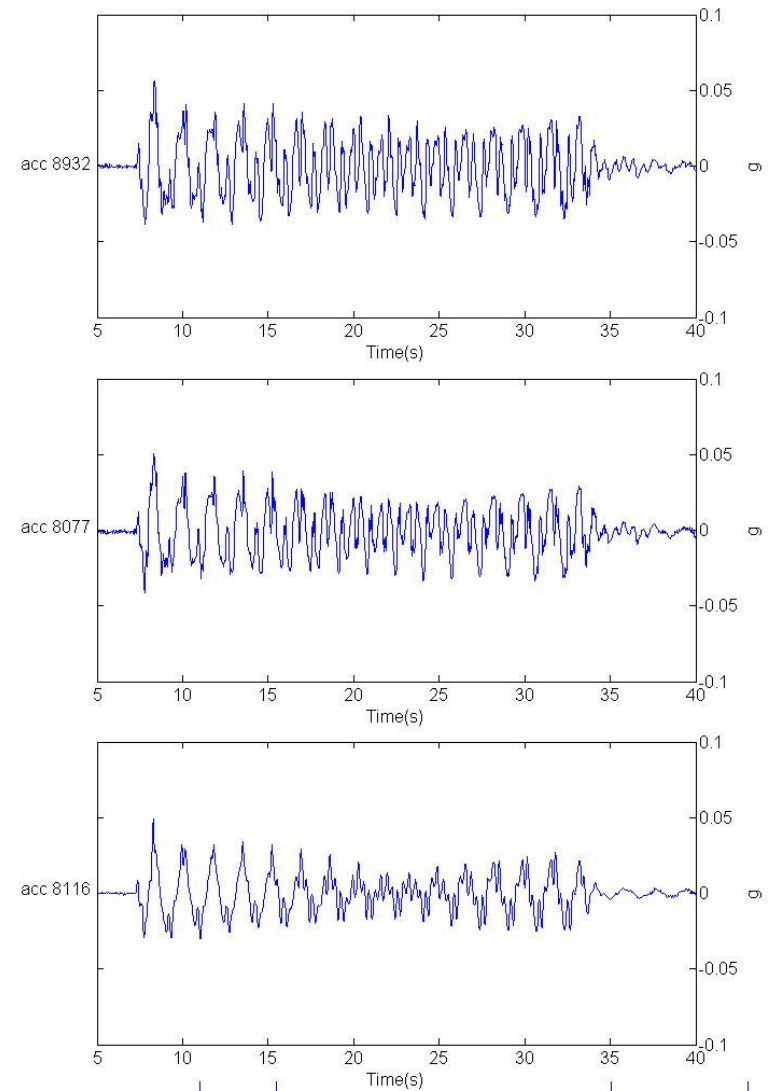
Figure No.

FLIGHT 1

Short-Term Time Records

1

Accelerations away from structure and box (input) acceleration



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

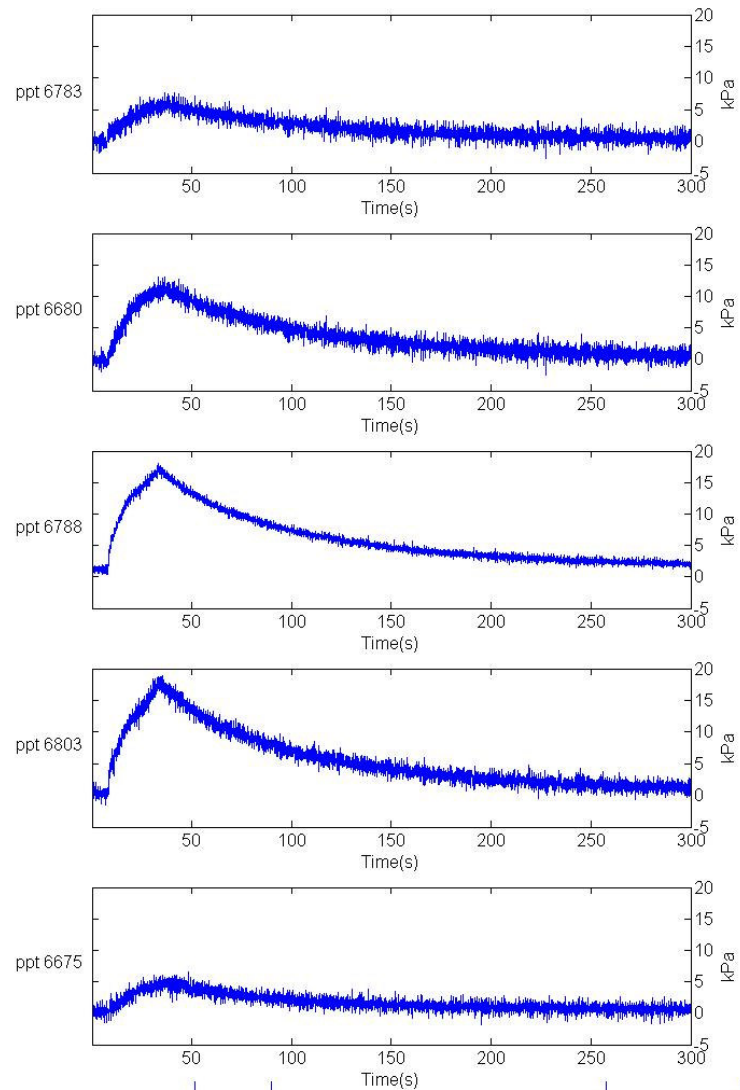
Figure No.

FLIGHT 1

Short-Term Time Records

1

Excess pore pressures under structure and between micro-piles



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

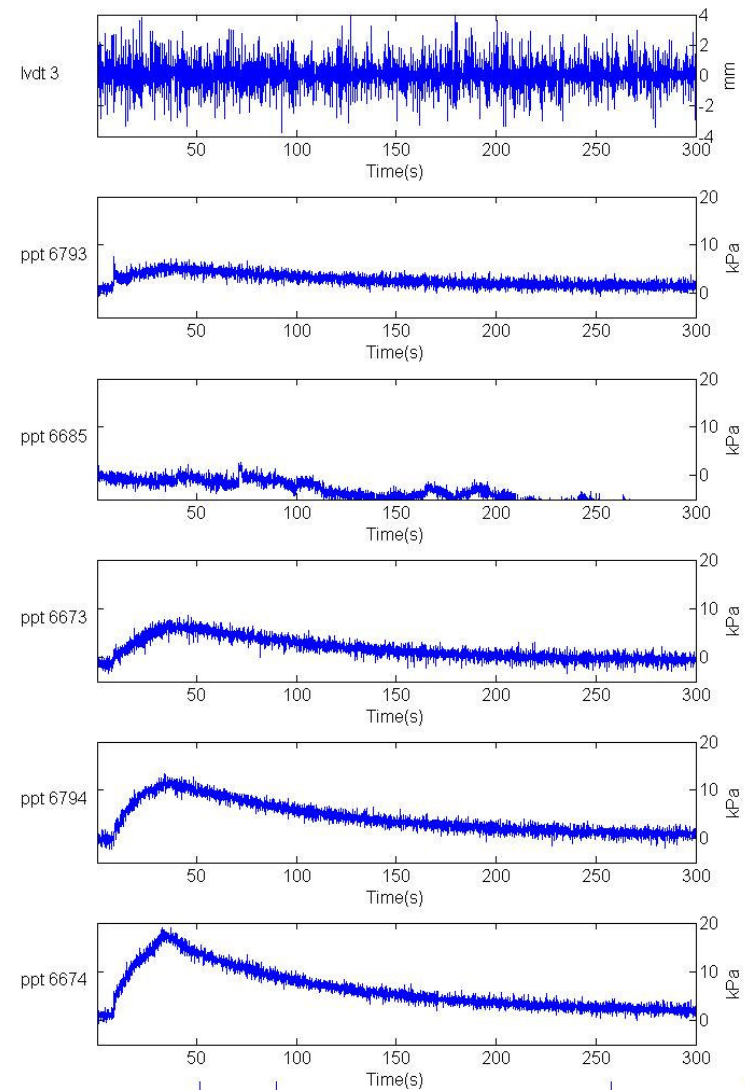
Figure No.

FLIGHT 1

Long-Term Time Records

1

Excess pore pressures away from structure and soil settlement



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

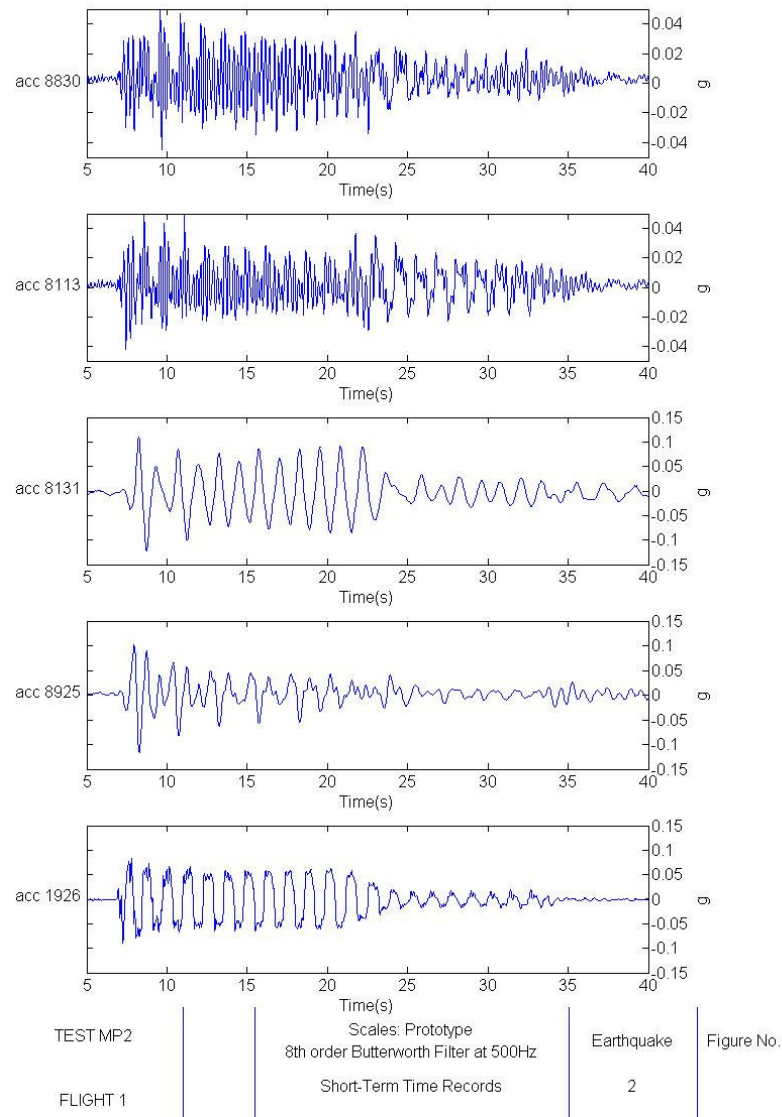
FLIGHT 1

Long-Term Time Records

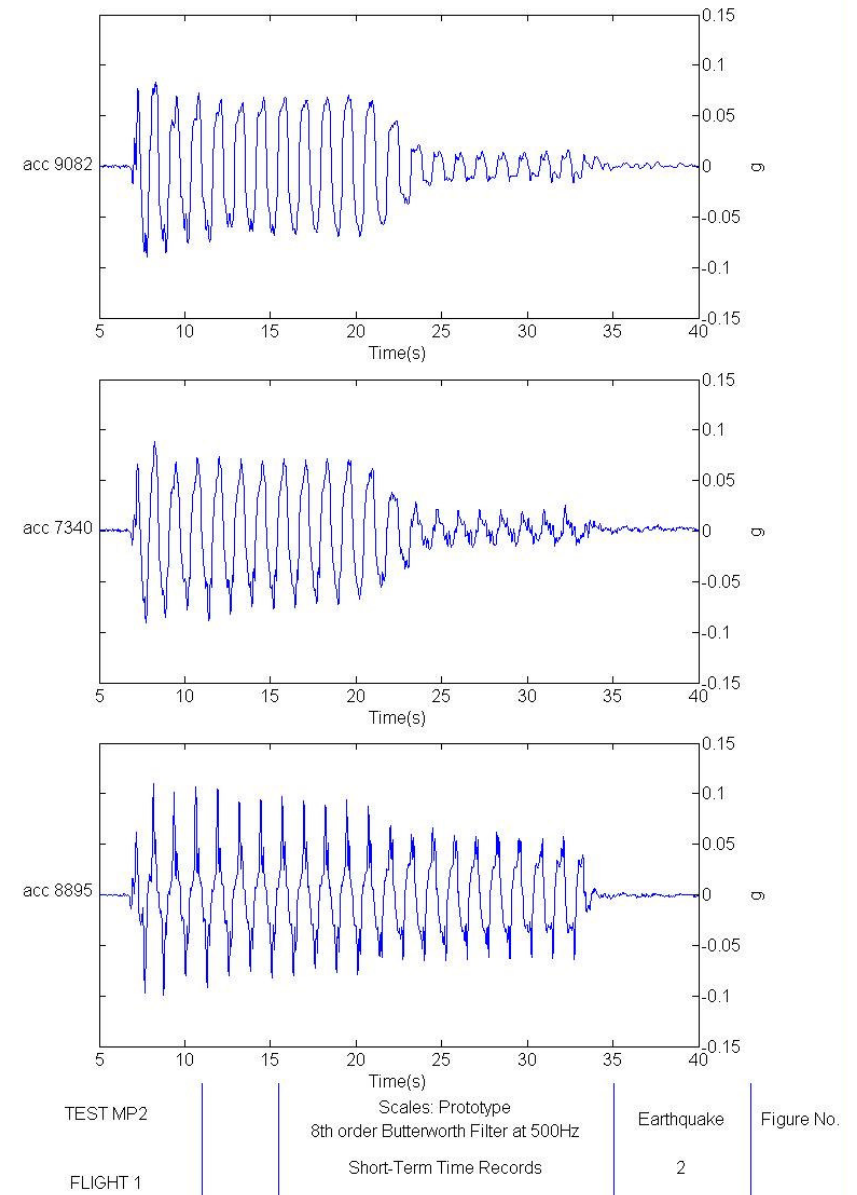
1

5.7 Centrifuge test MP2, earthquake 2

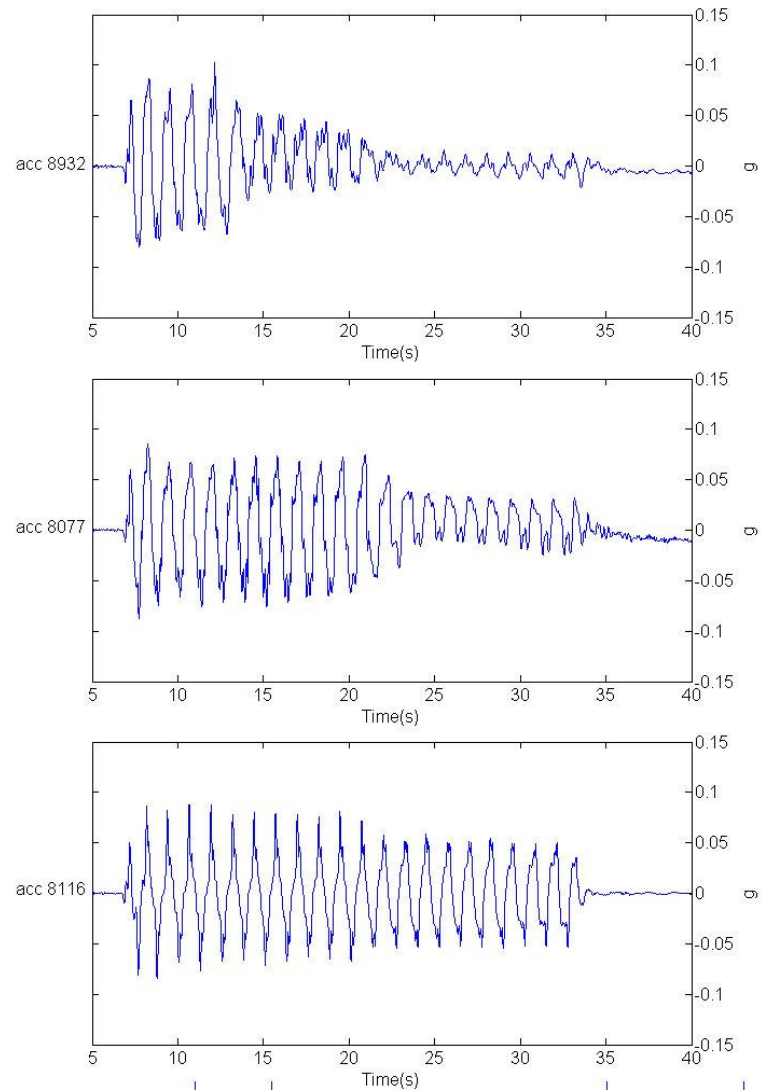
Vertical and horizontal structural accelerations



Accelerations under structure



Accelerations away from structure and box (input) acceleration



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

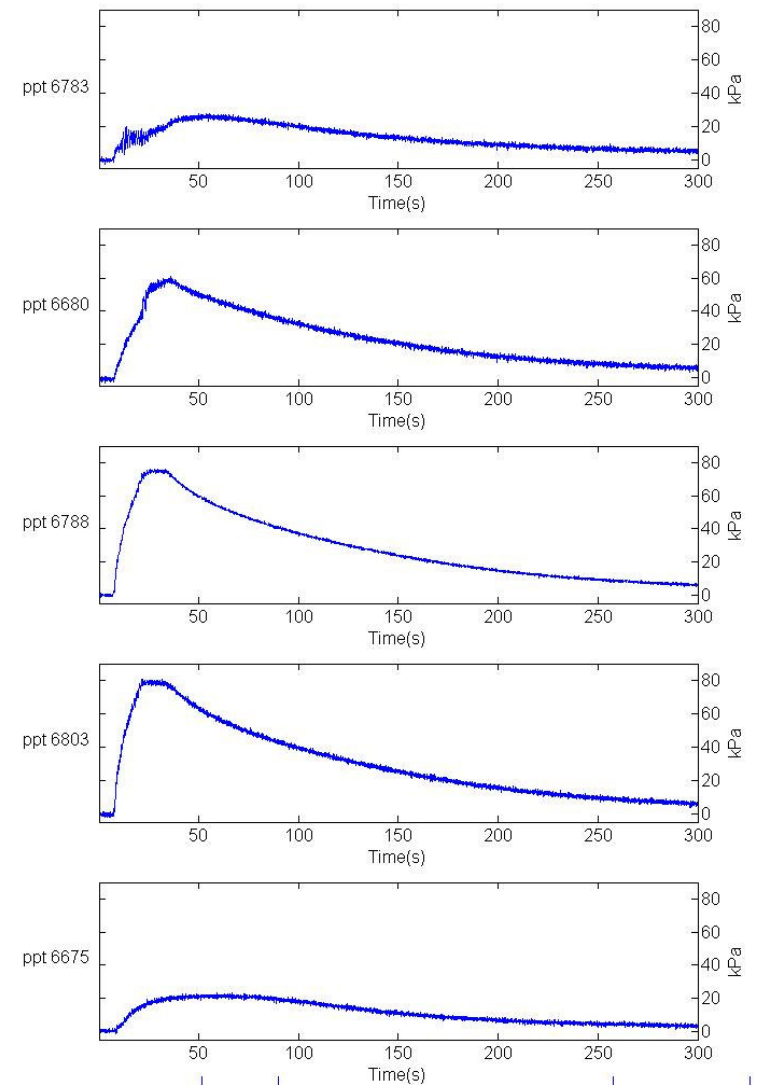
Figure No.

FLIGHT 1

Short-Term Time Records

2

Excess pore pressures under structure and between micro-piles



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

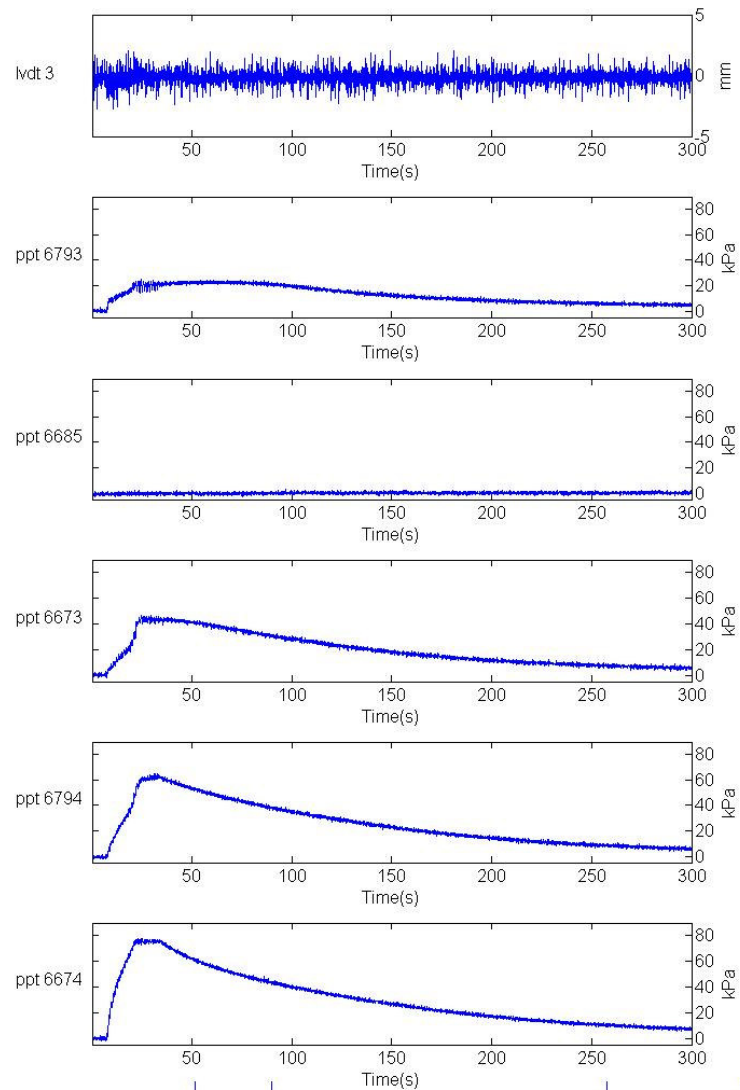
Figure No.

FLIGHT 1

Long-Term Time Records

2

Excess pore pressures away from structure and soil settlement



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

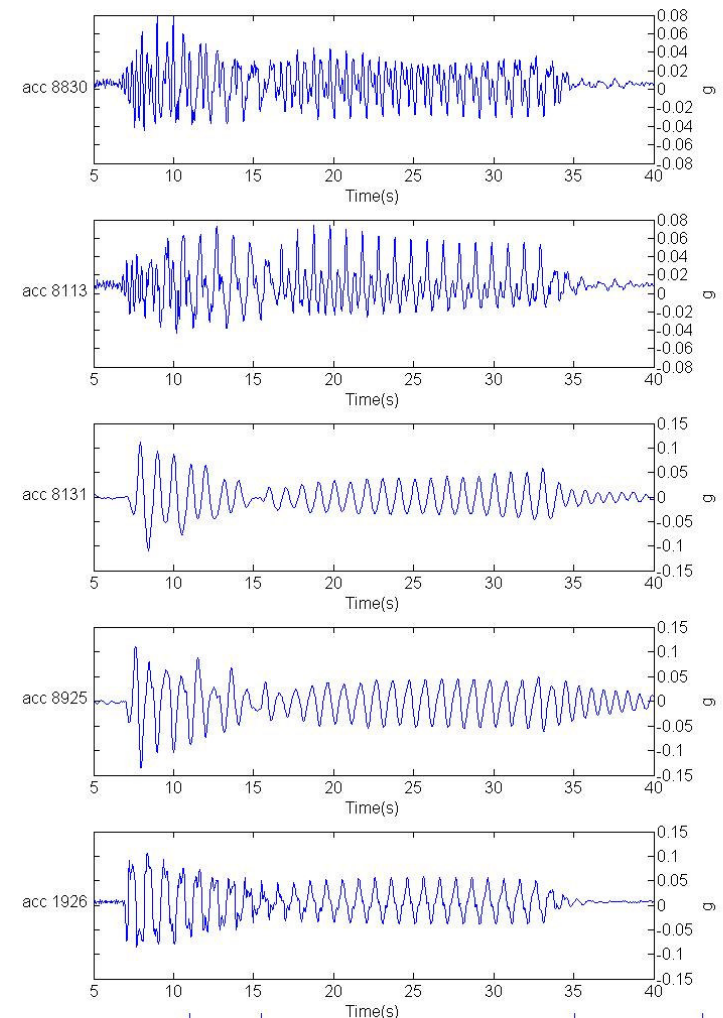
FLIGHT 1

Long-Term Time Records

2

5.8 Centrifuge test MP2, earthquake 3

Vertical and horizontal structural accelerations



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

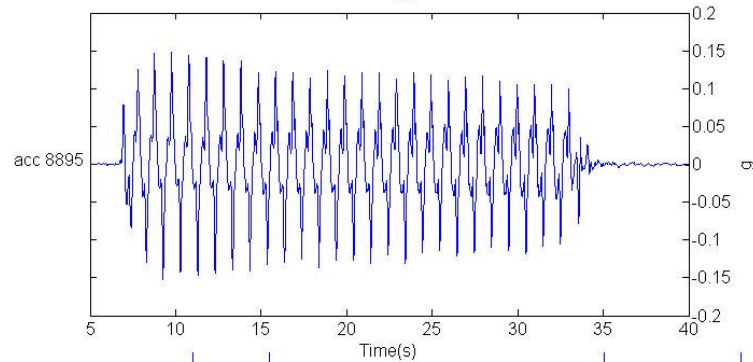
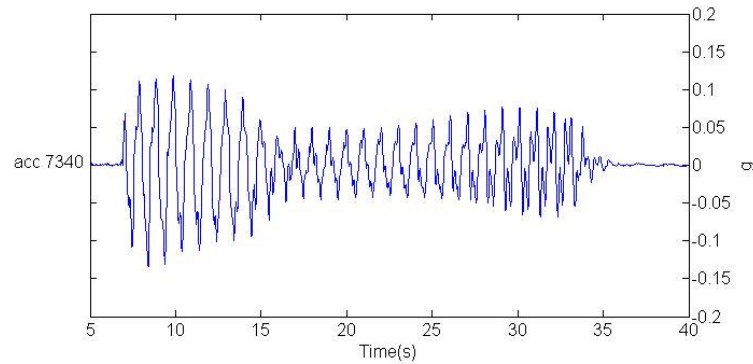
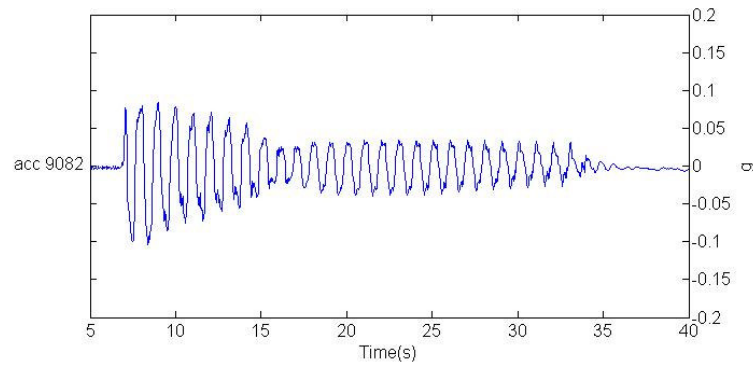
Figure No.

FLIGHT 1

Short-Term Time Records

3

Accelerations under structure



TEST MP2

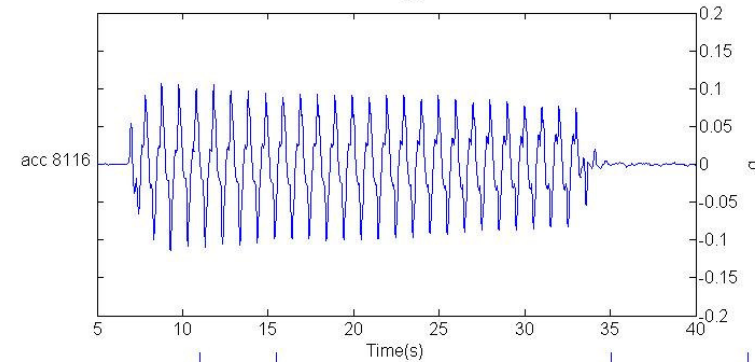
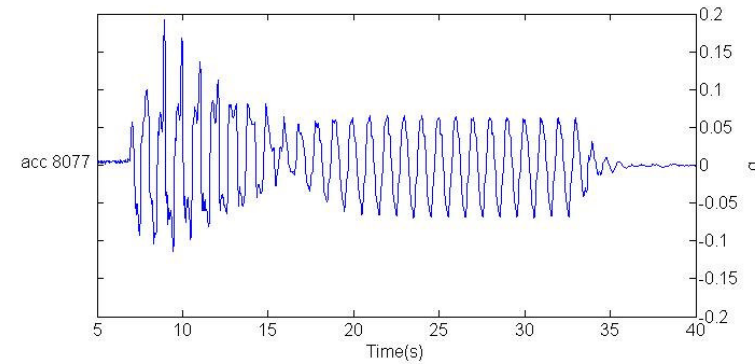
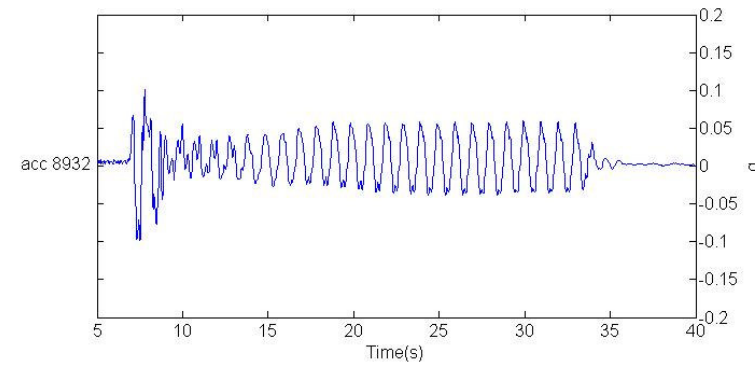
FLIGHT 1

Scales: Prototype
8th order Butterworth Filter at 500Hz
Short-Term Time Records

Earthquake
3

Figure No.

Accelerations away from structure and box (input) acceleration



TEST MP2

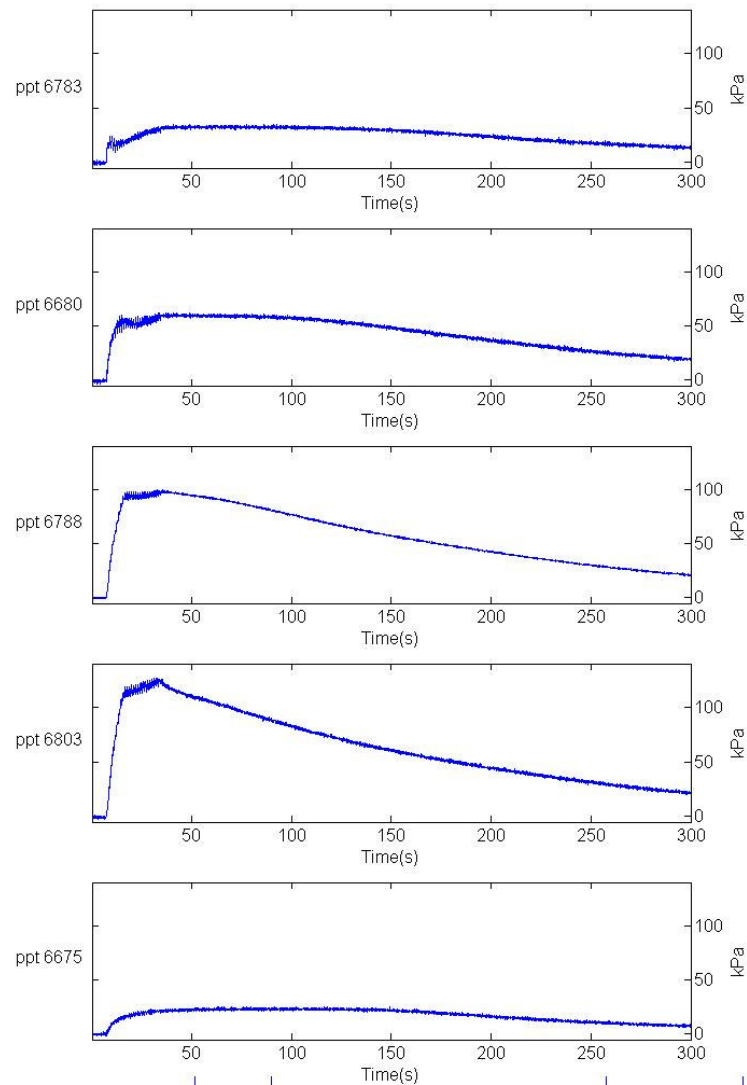
FLIGHT 1

Scales: Prototype
8th order Butterworth Filter at 500Hz
Short-Term Time Records

Earthquake
3

Figure No.

Excess pore pressures under structure and between micro-piles



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

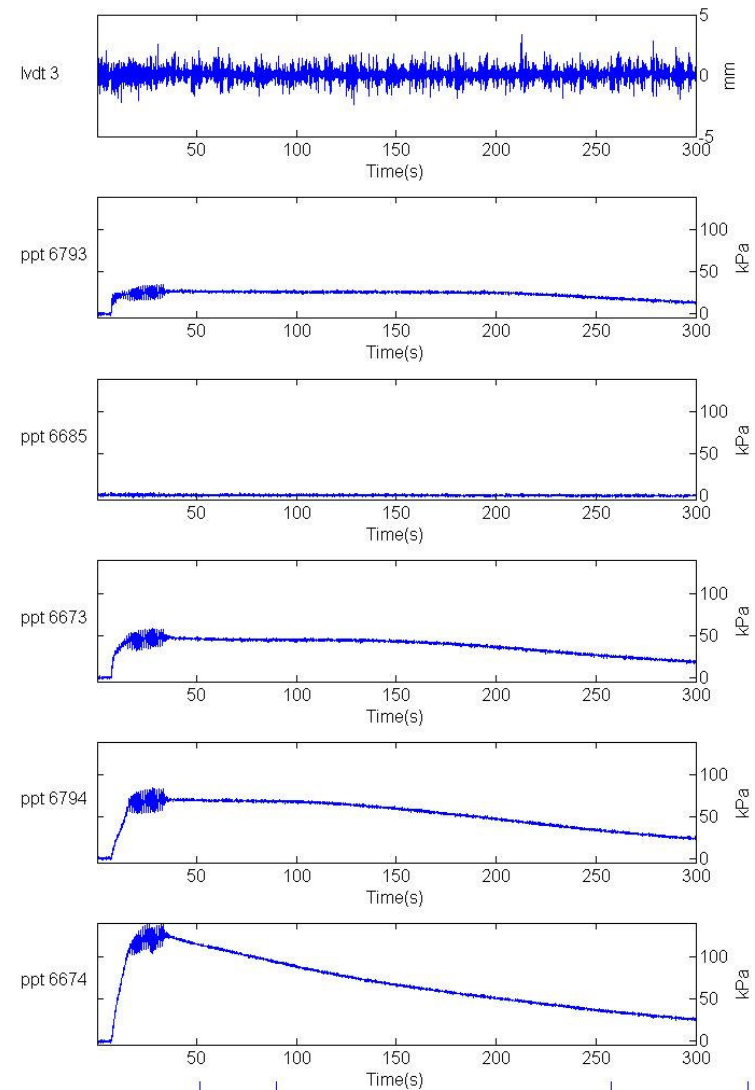
Figure No.

FLIGHT 1

Long-Term Time Records

3

Excess pore pressures away from structure and soil settlement



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

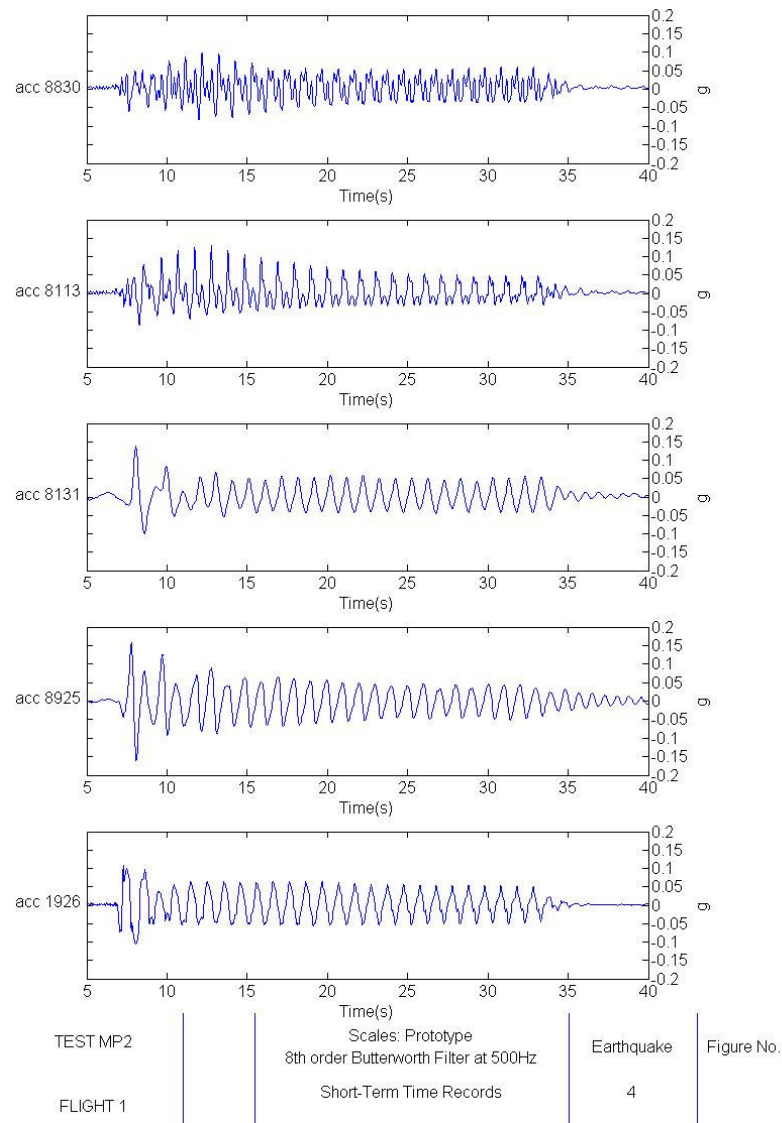
FLIGHT 1

Long-Term Time Records

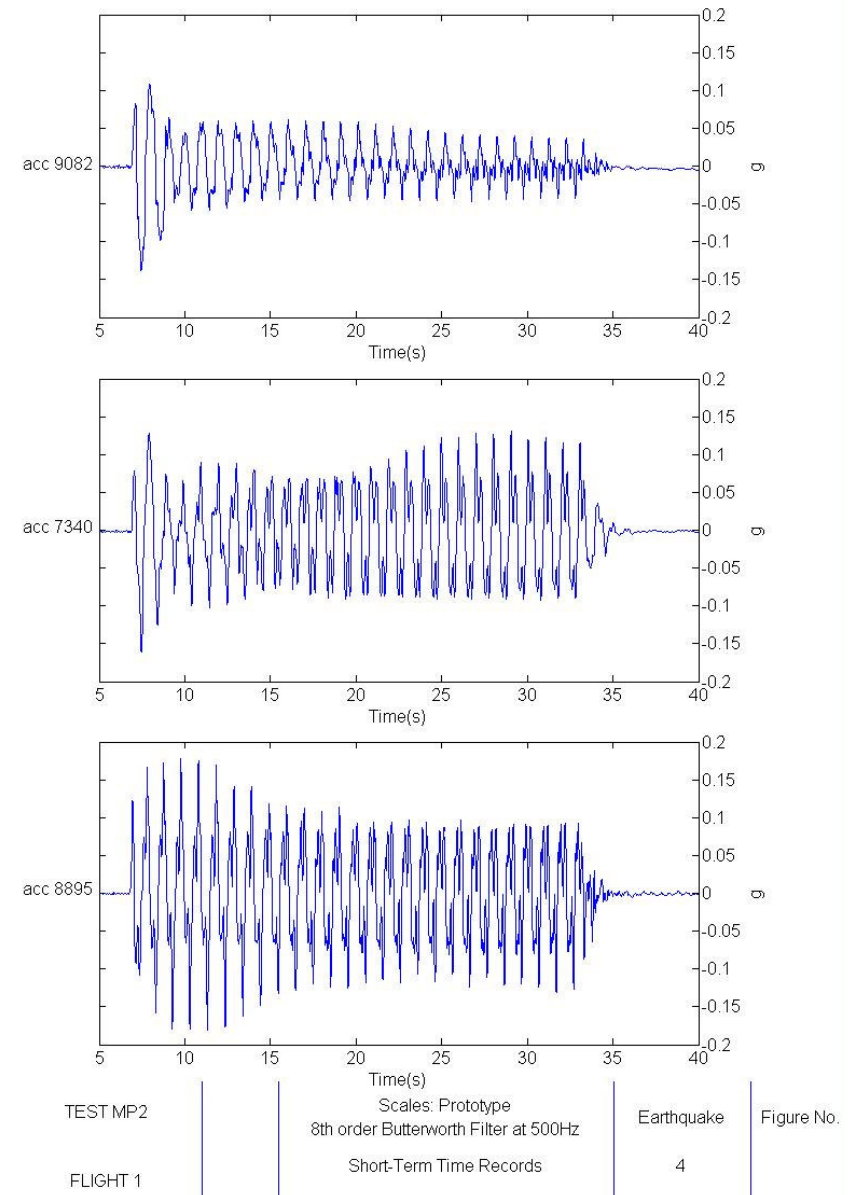
3

5.9 Centrifuge test MP2, earthquake 4

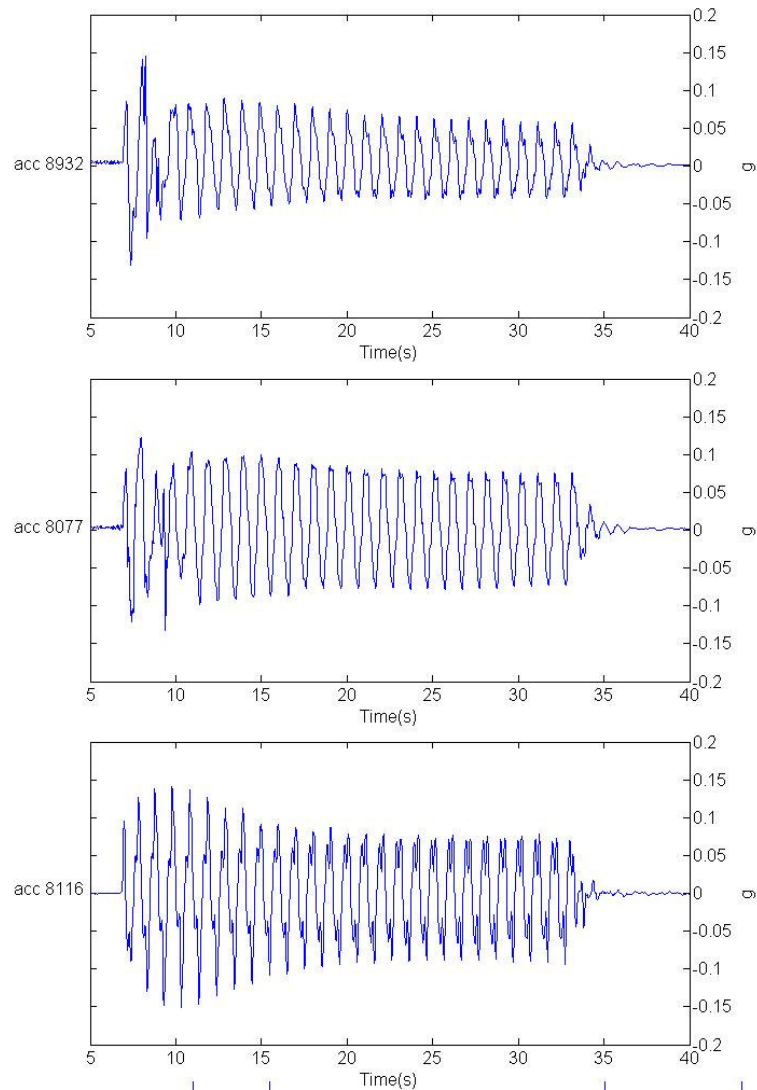
Vertical and horizontal structural accelerations



Accelerations under structure



Accelerations away from structure and box (input) acceleration



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

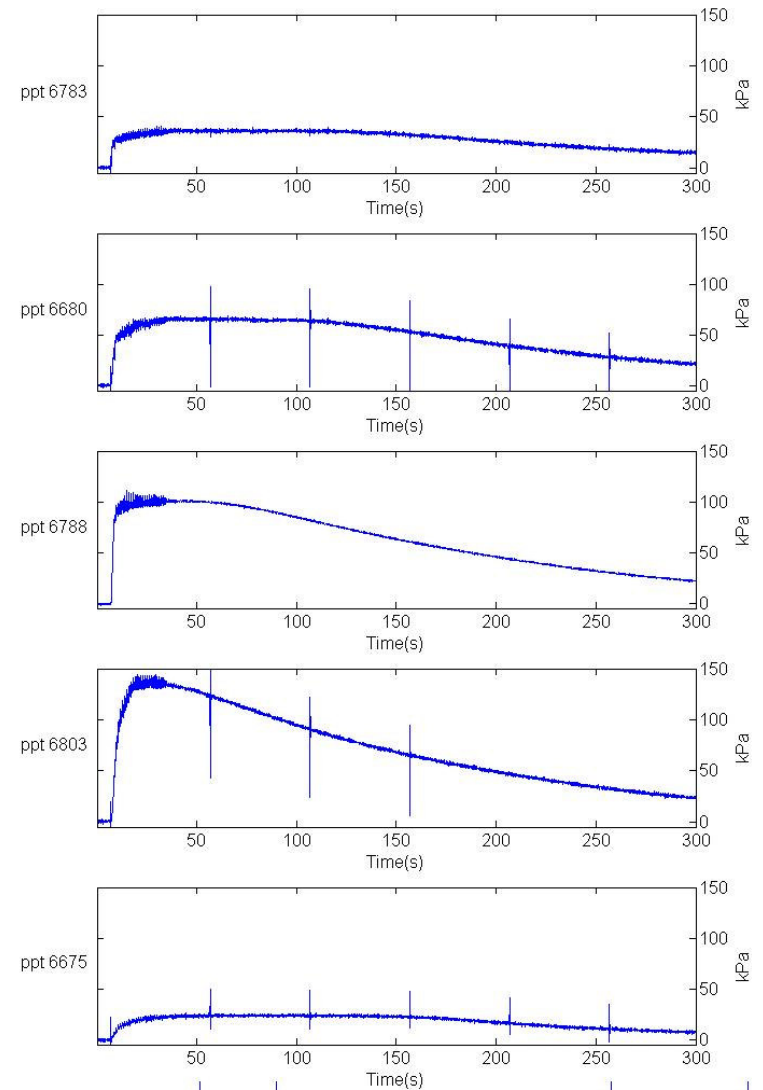
Figure No.

FLIGHT 1

Short-Term Time Records

4

Excess pore pressures under structure and between micro-piles



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

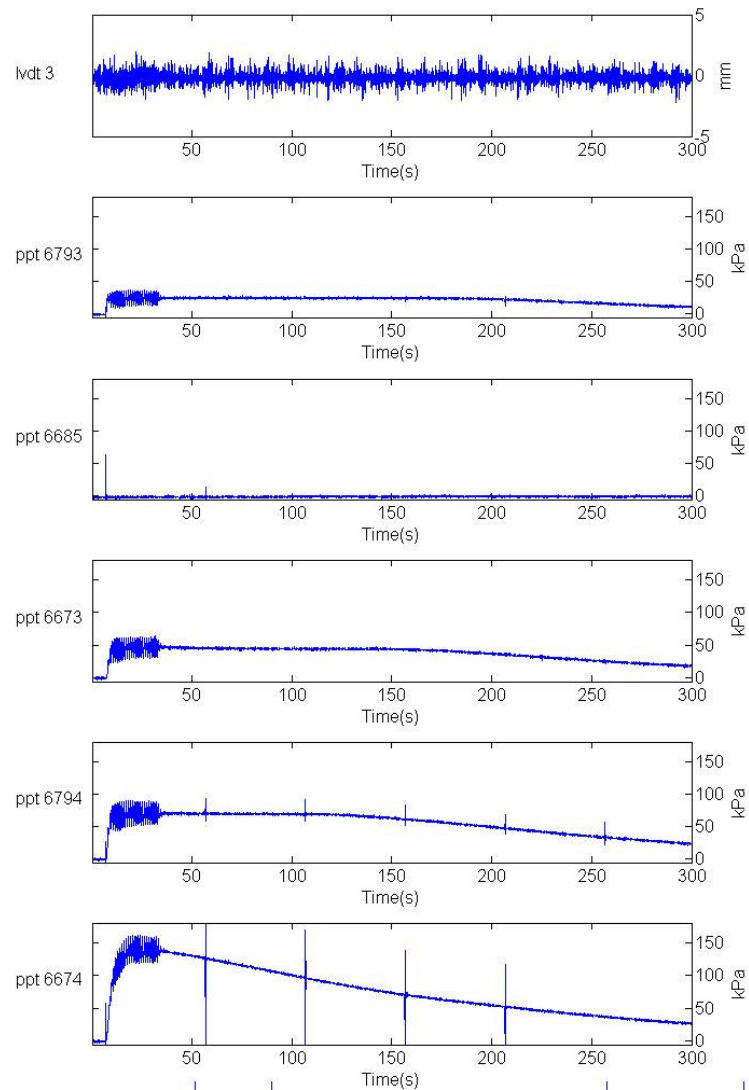
Figure No.

FLIGHT 1

Long-Term Time Records

4

Excess pore pressures away from structure and soil settlement



TEST MP2

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

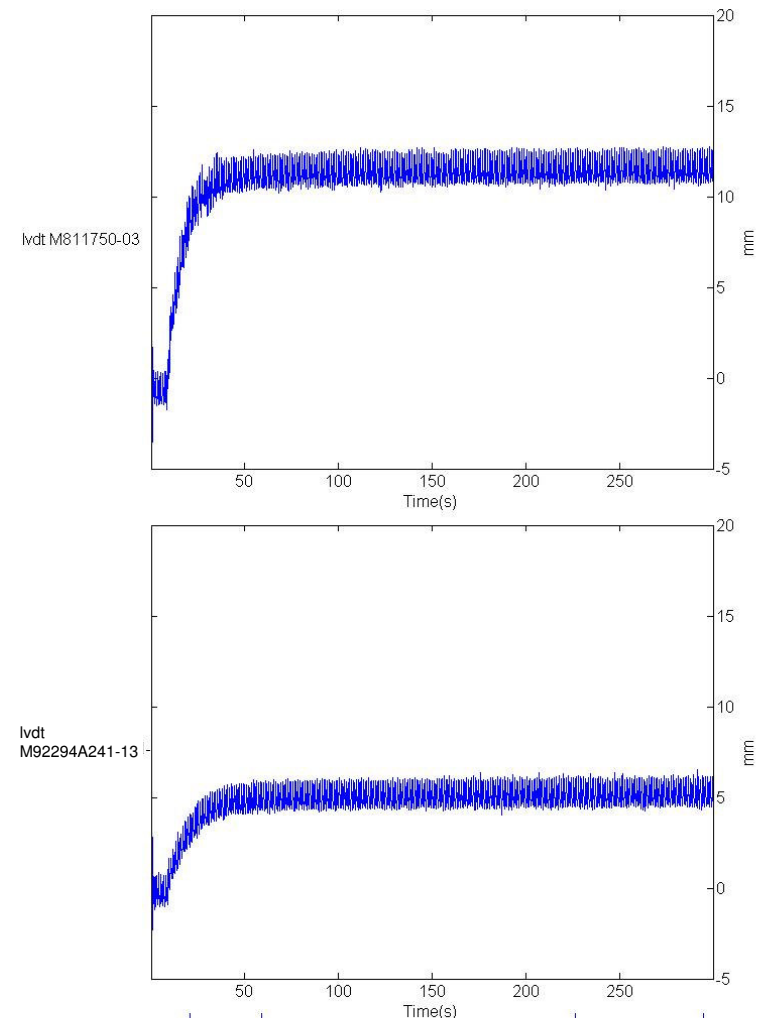
FLIGHT 1

Long-Term Time Records

4

5.10 Centrifuge test MP3, earthquake 1

Soil surface and structural settlement



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

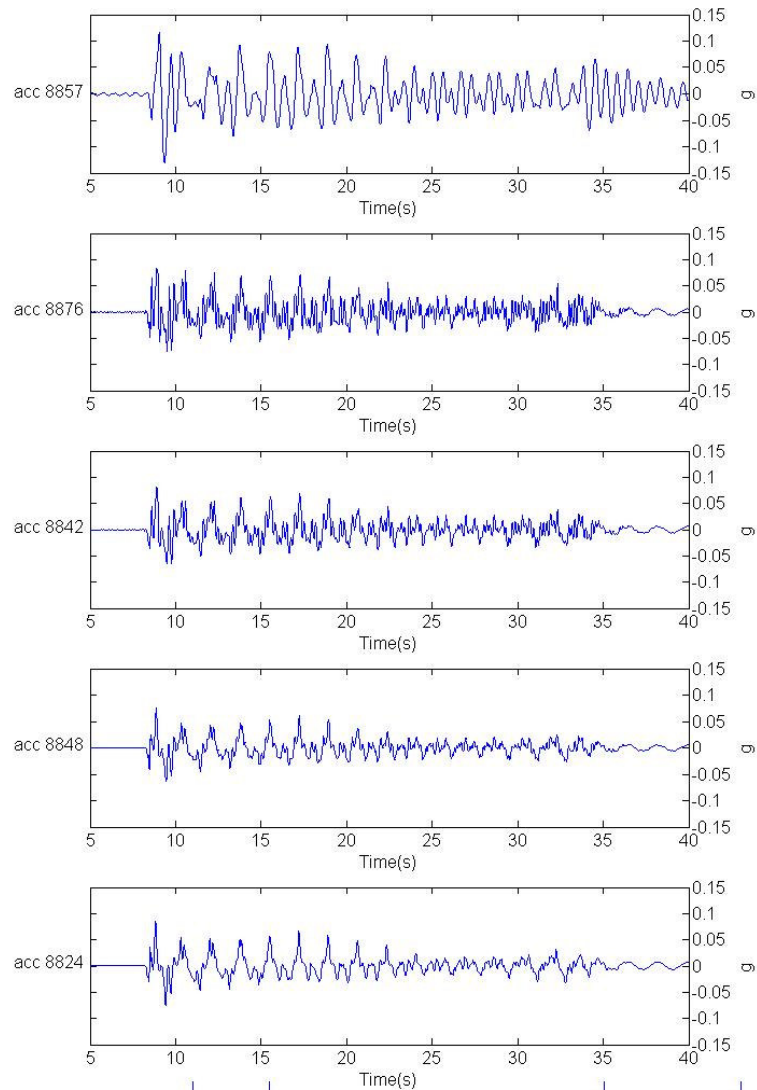
Figure No.

FLIGHT 1

Long-Term Time Records

1

Accelerations of structure and soil under structure



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

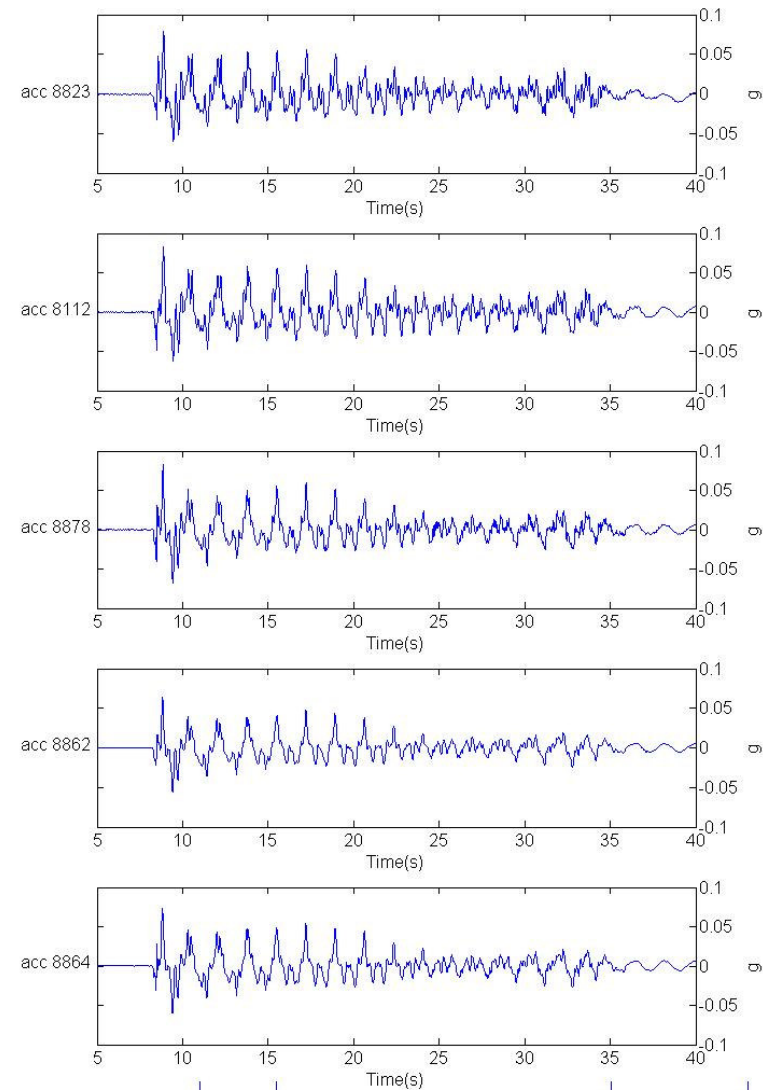
Figure No.

FLIGHT 1

Short-Term Time Records

1

Accelerations away from structure and box (input) acceleration



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

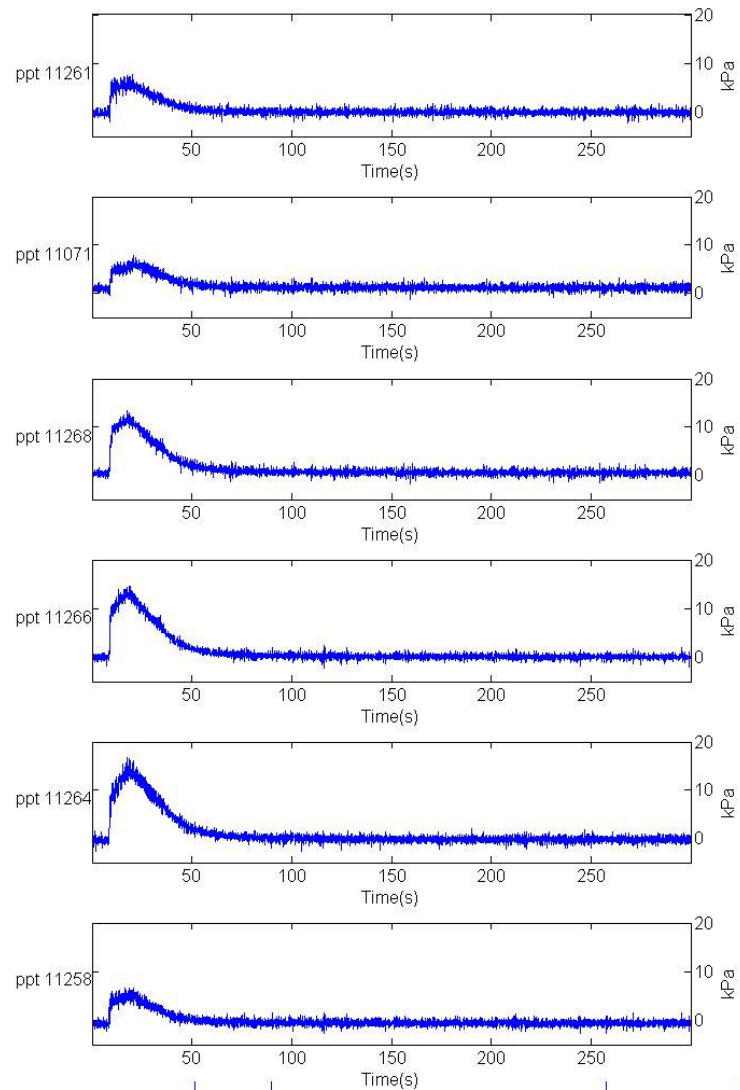
Figure No.

FLIGHT 1

Short-Term Time Records

1

Excess pore pressures under structure and between micro-piles



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

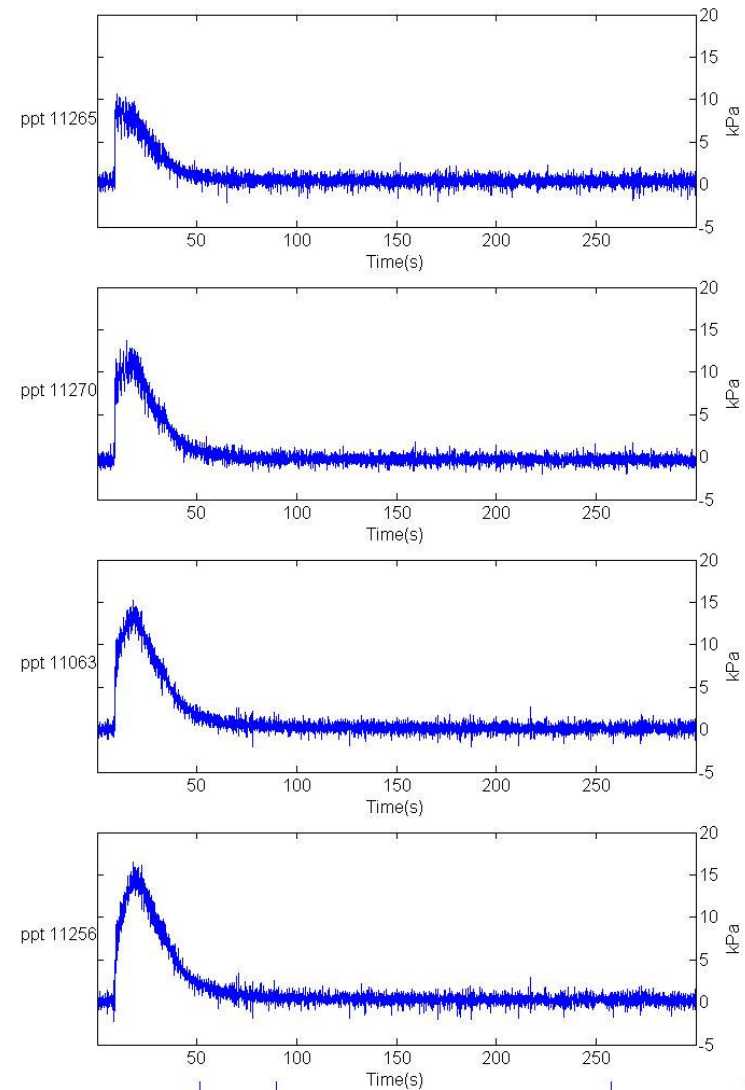
Figure No.

FLIGHT 1

Long-Term Time Records

1

Excess pore pressures away from structure



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

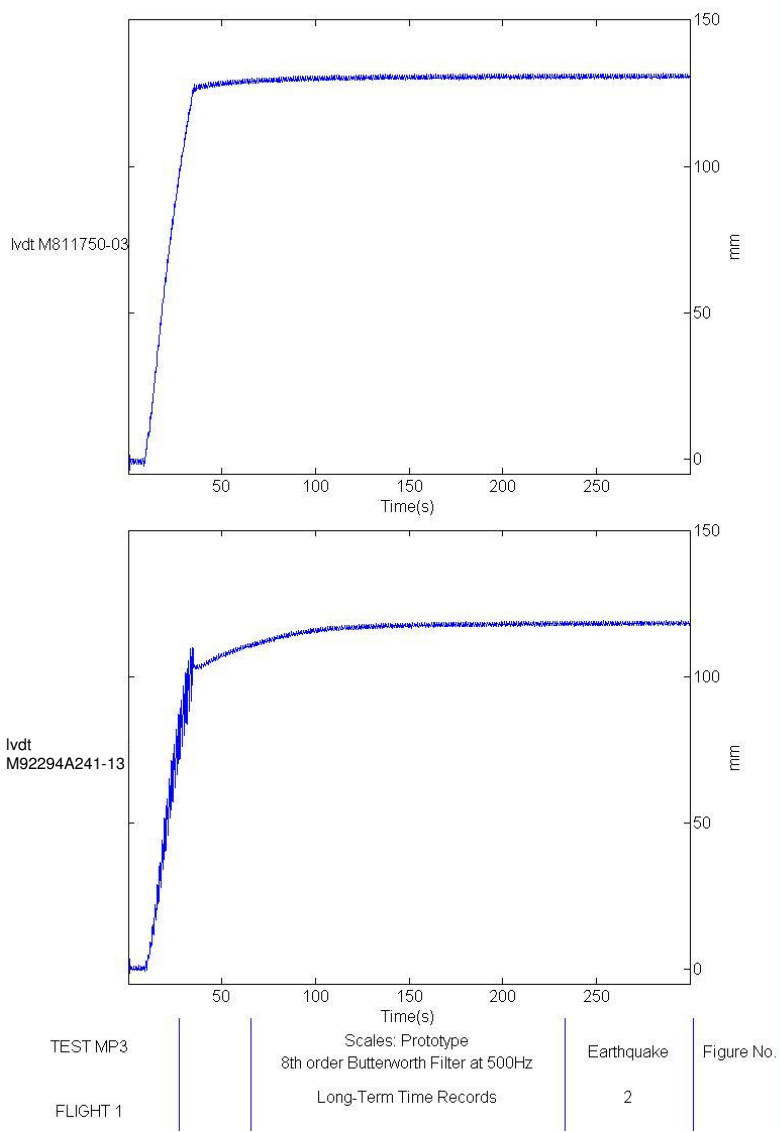
FLIGHT 1

Long-Term Time Records

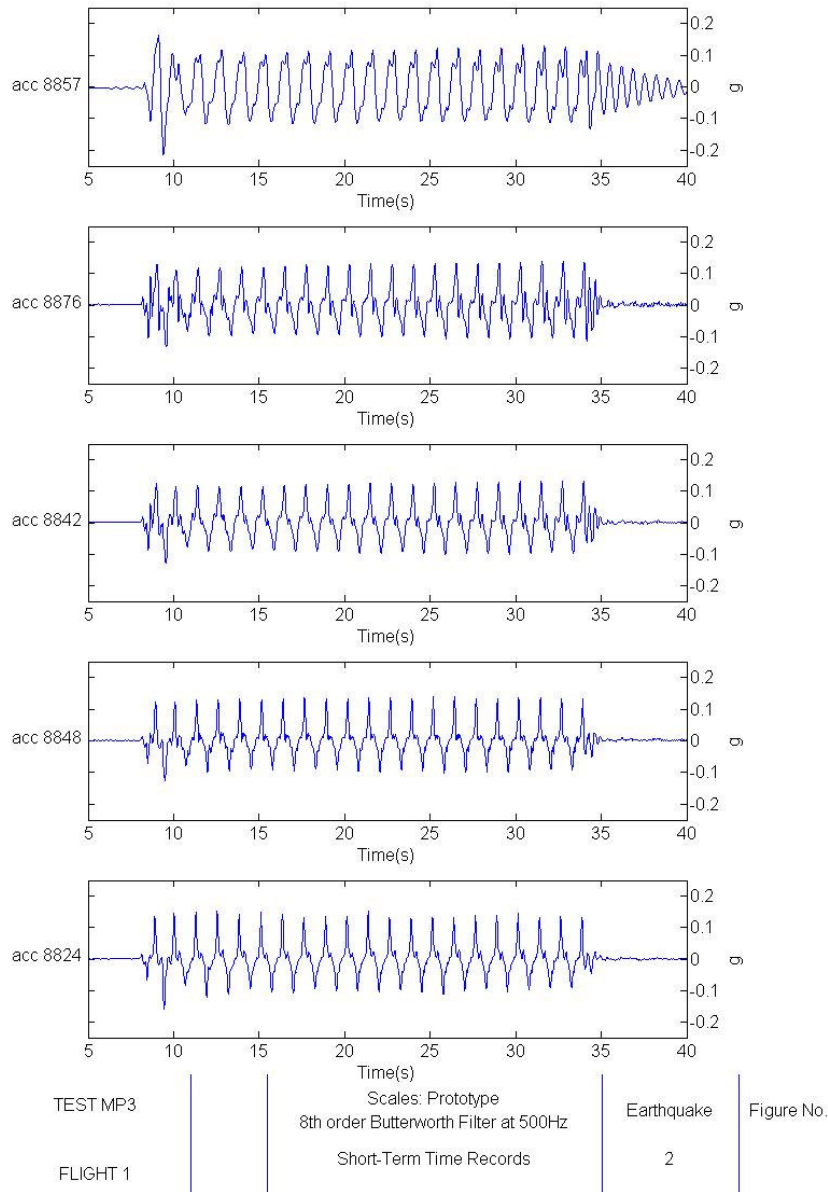
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5.11 Centrifuge test MP3, earthquake 2

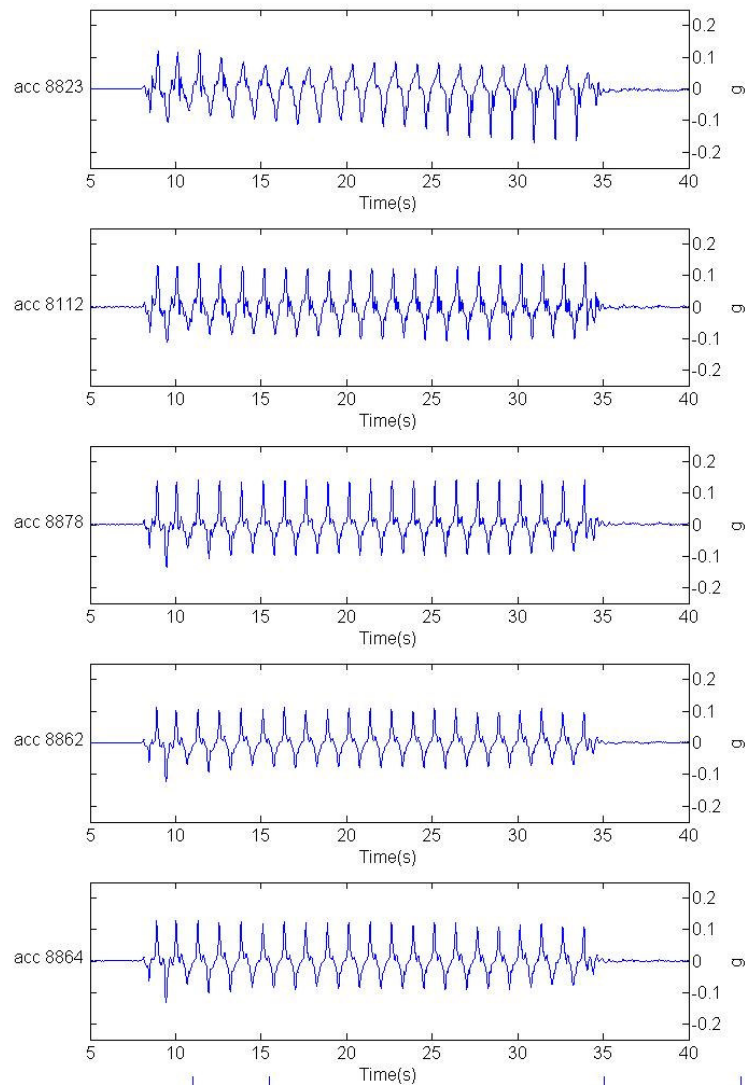
Soil surface and structural settlement



Accelerations of structure and soil under structure



Accelerations away from structure and box (input) acceleration



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

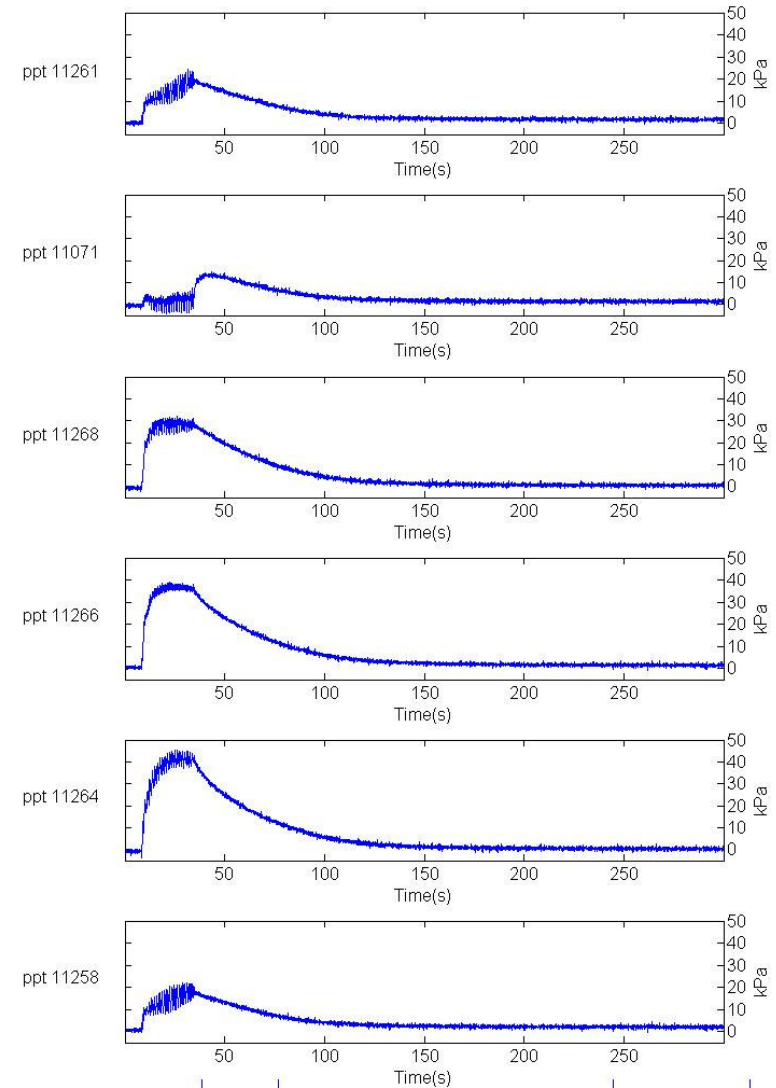
Figure No.

FLIGHT 1

Short-Term Time Records

2

Excess pore pressures under structure and between micro-piles



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

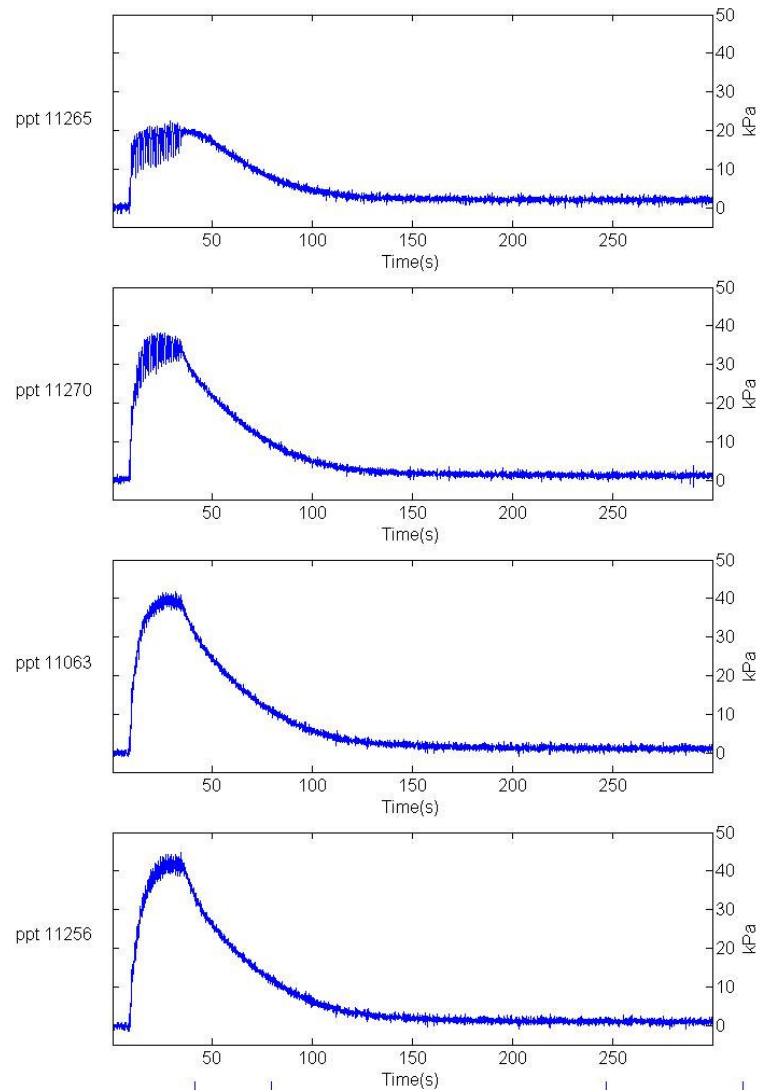
Figure No.

FLIGHT 1

Long-Term Time Records

2

Excess pore pressures away from structure



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

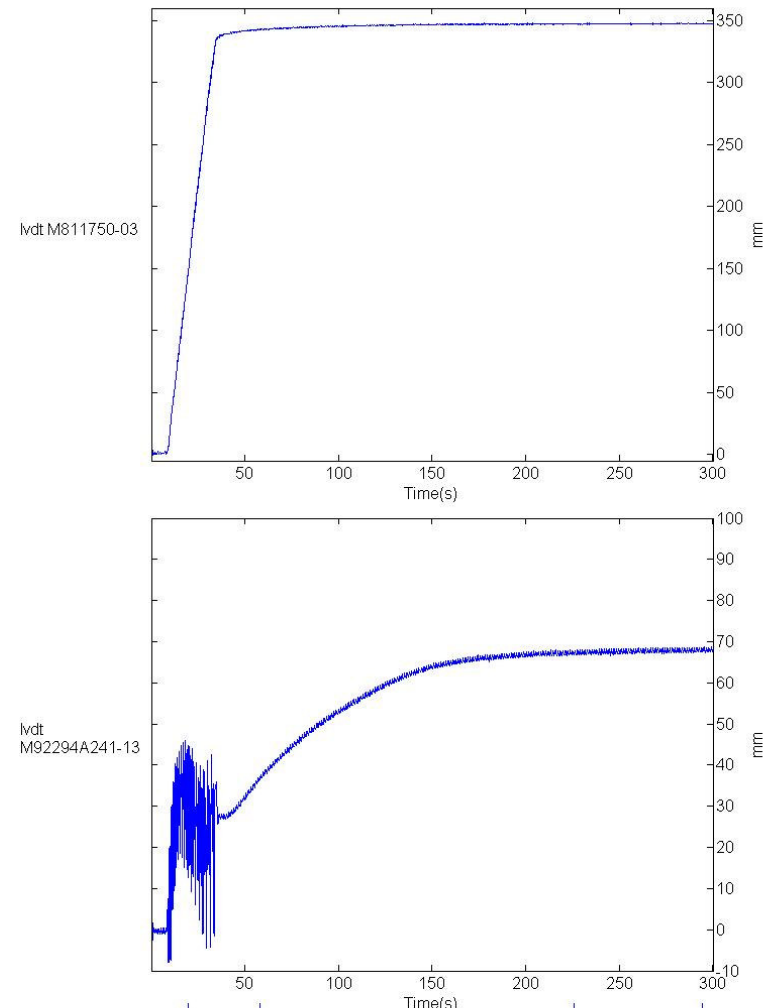
FLIGHT 1

Long-Term Time Records

2

5.12 Centrifuge test MP3, earthquake 3

Soil surface and structural settlement



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

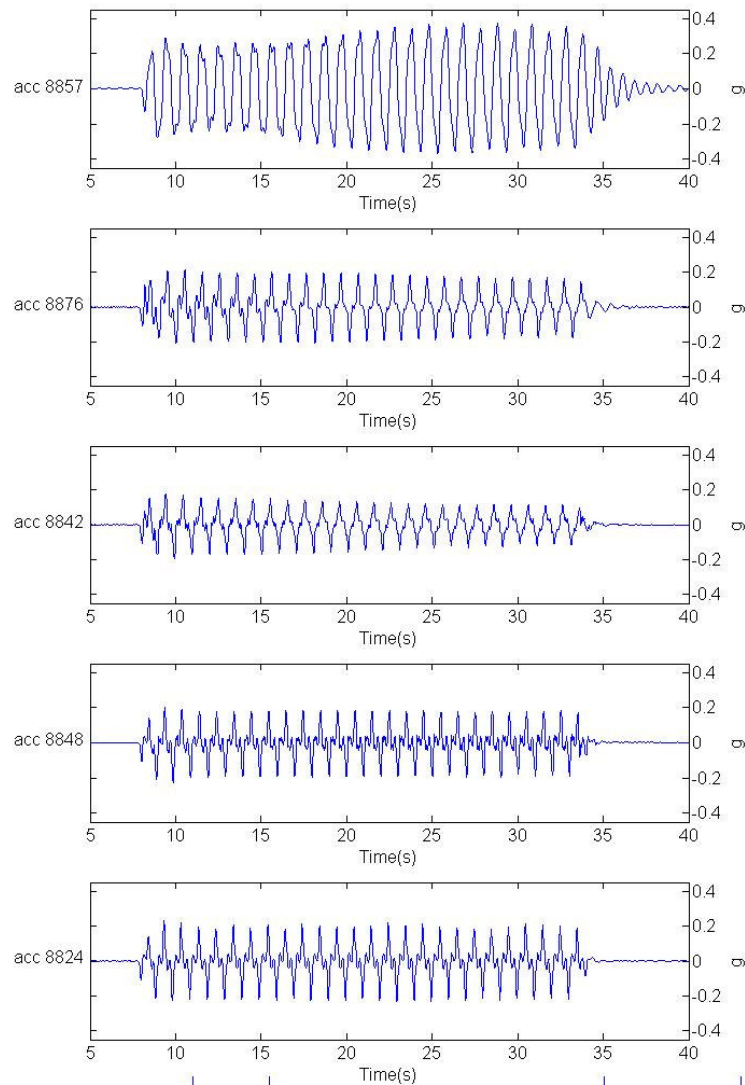
Figure No.

FLIGHT 1

Long-Term Time Records

3

Accelerations of structure and soil under structure



TEST MP3

FLIGHT 1

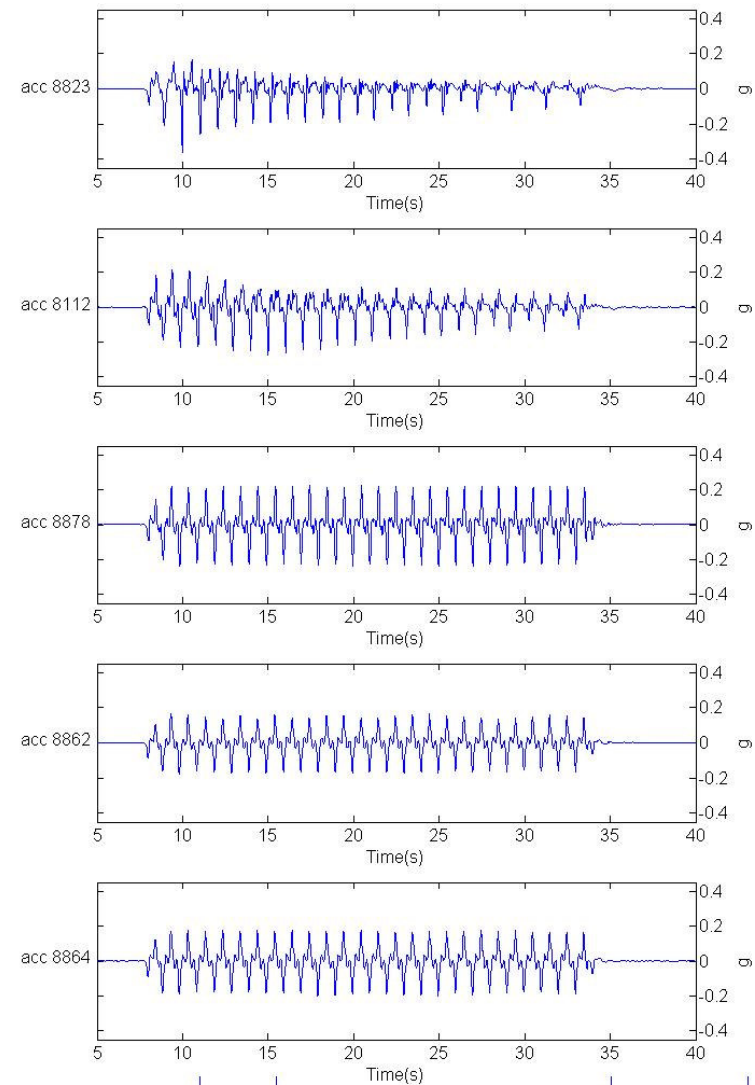
Scales: Prototype
8th order Butterworth Filter at 500Hz
Short-Term Time Records

Earthquake

3

Figure No.

Accelerations away from structure and box (input) acceleration



TEST MP3

FLIGHT 1

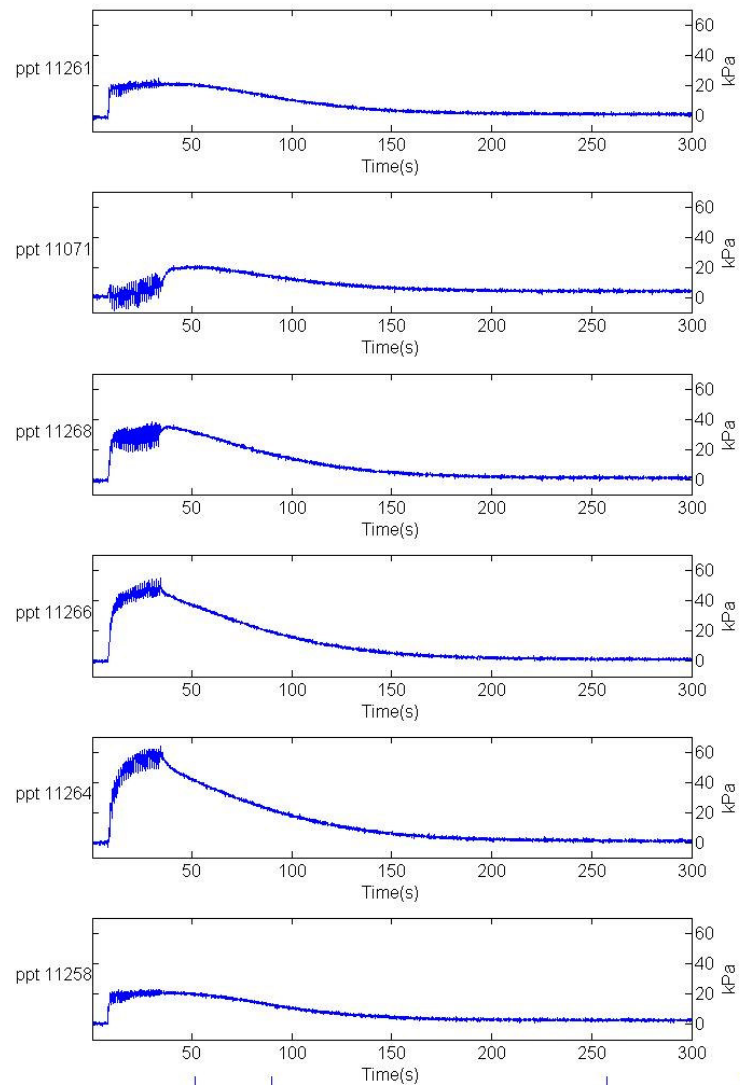
Scales: Prototype
8th order Butterworth Filter at 500Hz
Short-Term Time Records

Earthquake

3

Figure No.

Excess pore pressures under structure and between micro-piles



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

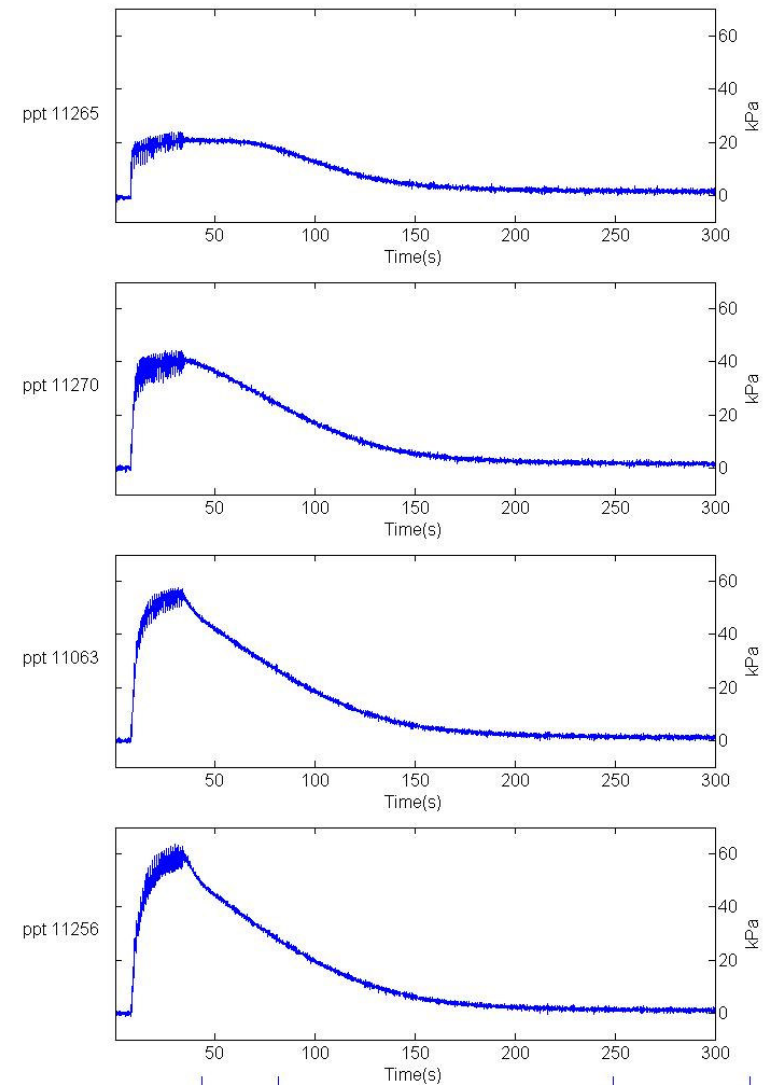
Figure No.

FLIGHT 1

Long-Term Time Records

3

Excess pore pressures away from structure



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

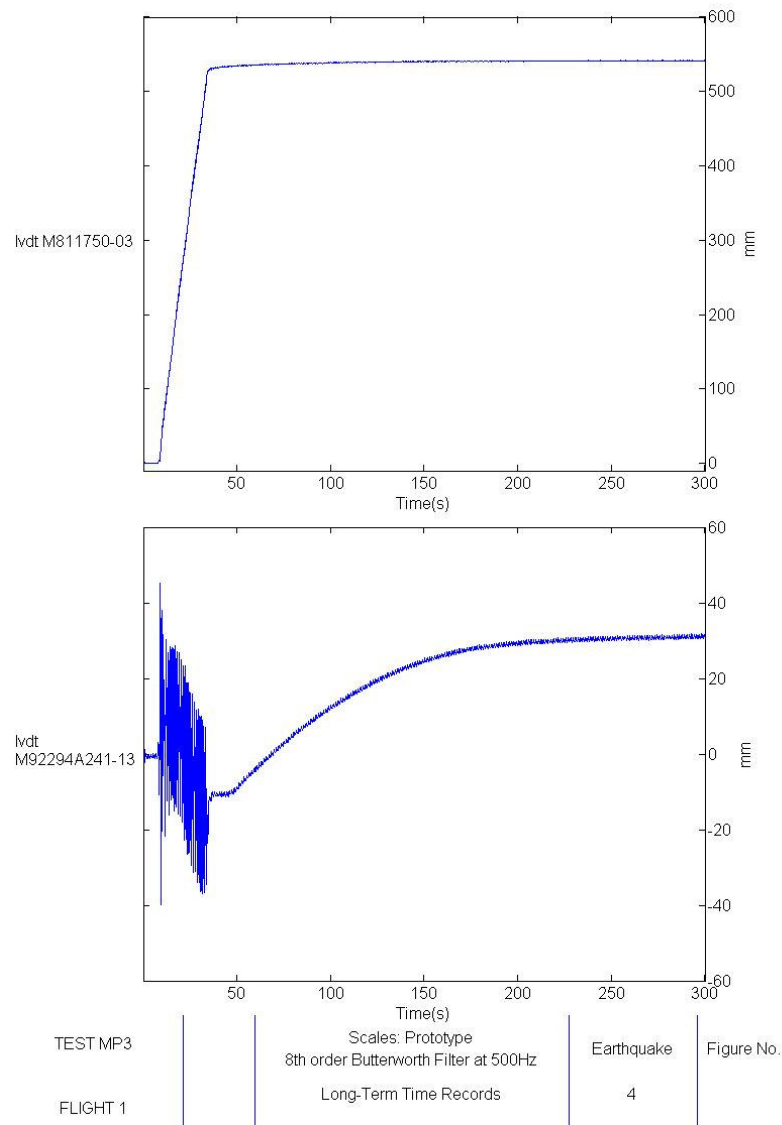
FLIGHT 1

Long-Term Time Records

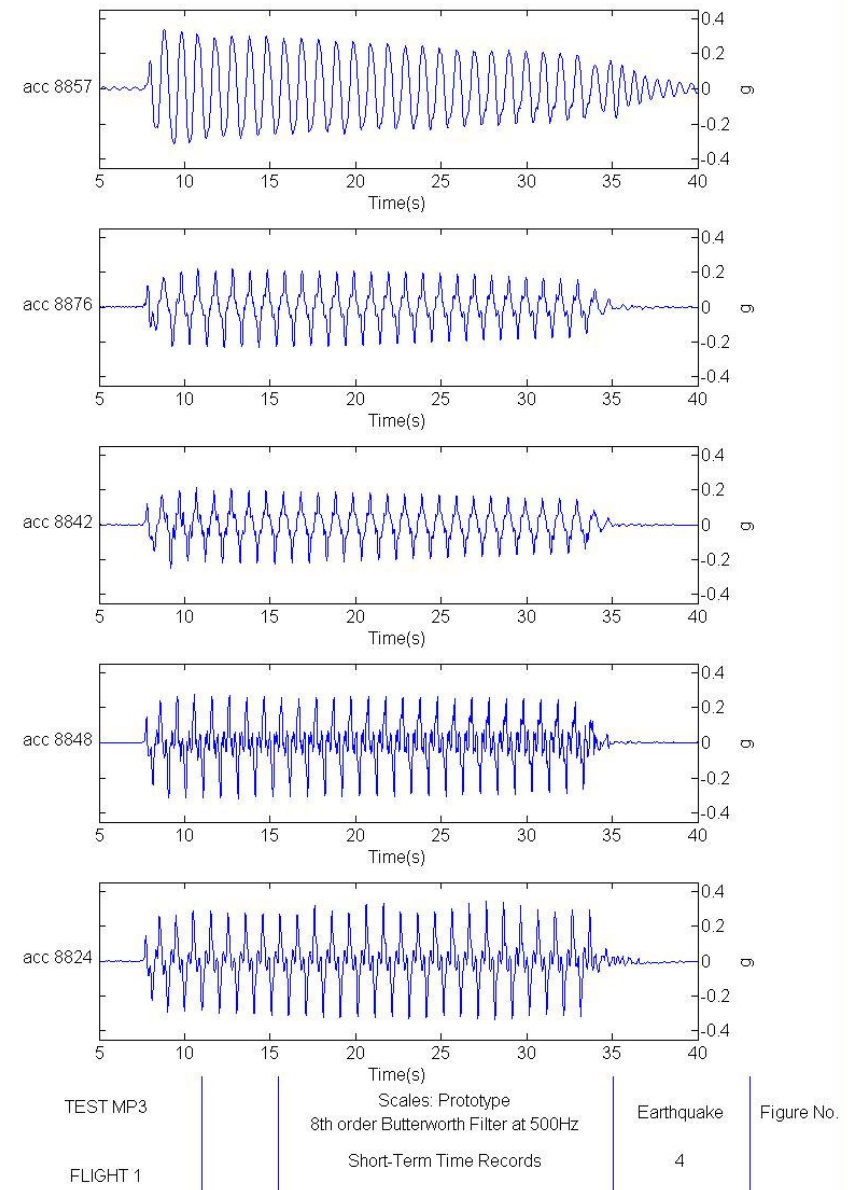
3

5.13 Centrifuge test MP3, earthquake 4

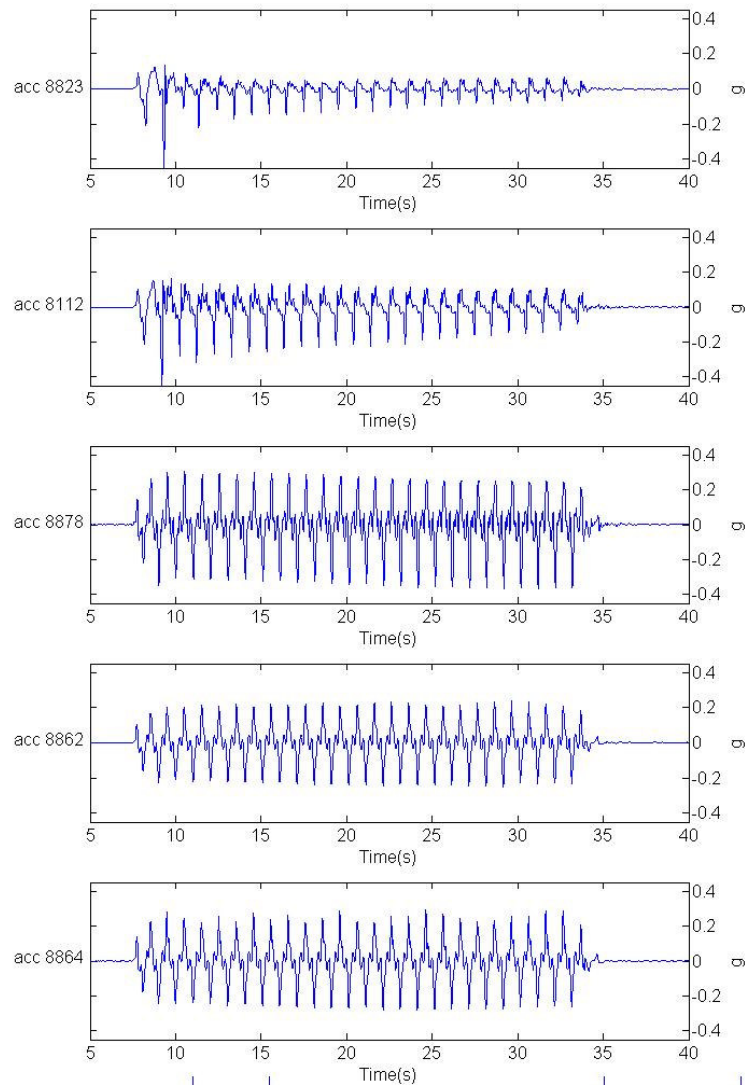
Soil surface and structural settlement



Accelerations of structure and soil under structure



Accelerations away from structure and box (input) acceleration



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

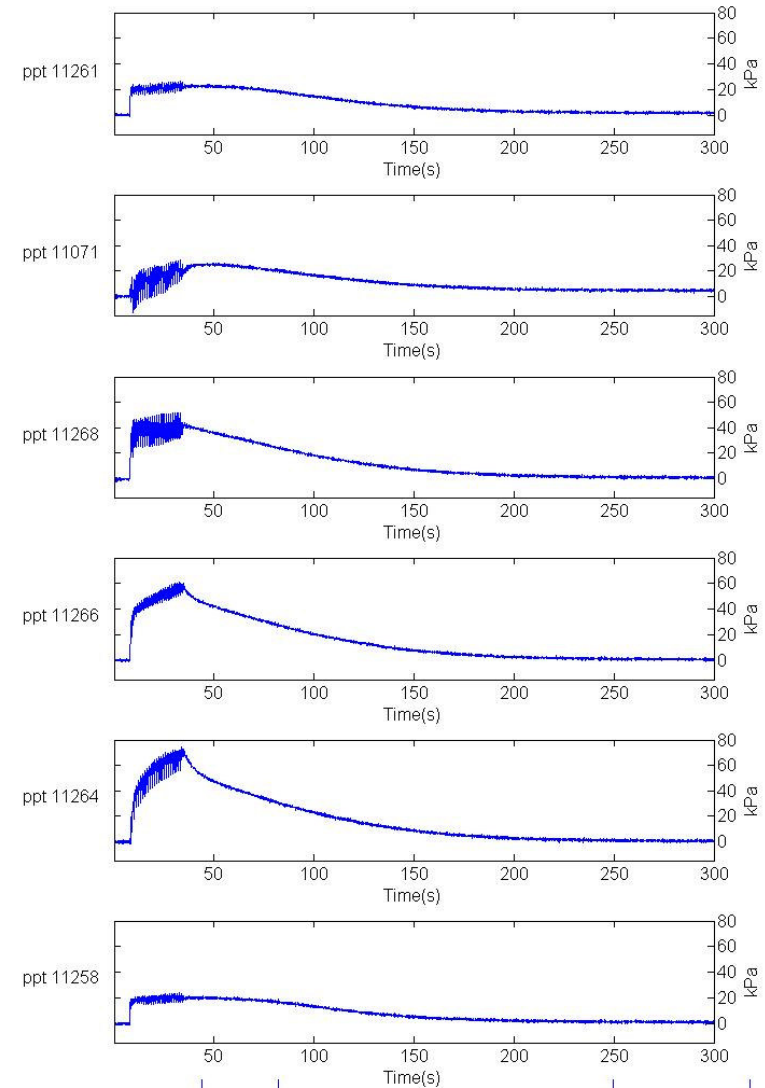
Figure No.

FLIGHT 1

Short-Term Time Records

4

Excess pore pressures under structure and between micro-piles



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

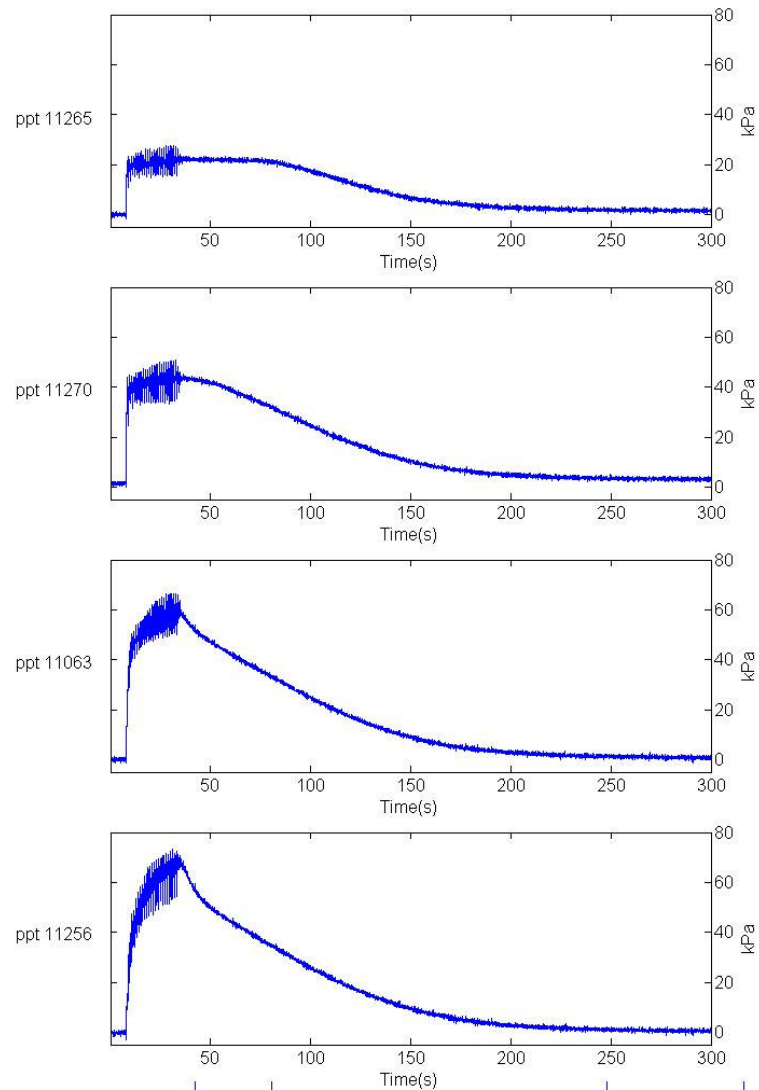
Figure No.

FLIGHT 1

Long-Term Time Records

4

Excess pore pressures away from structure



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

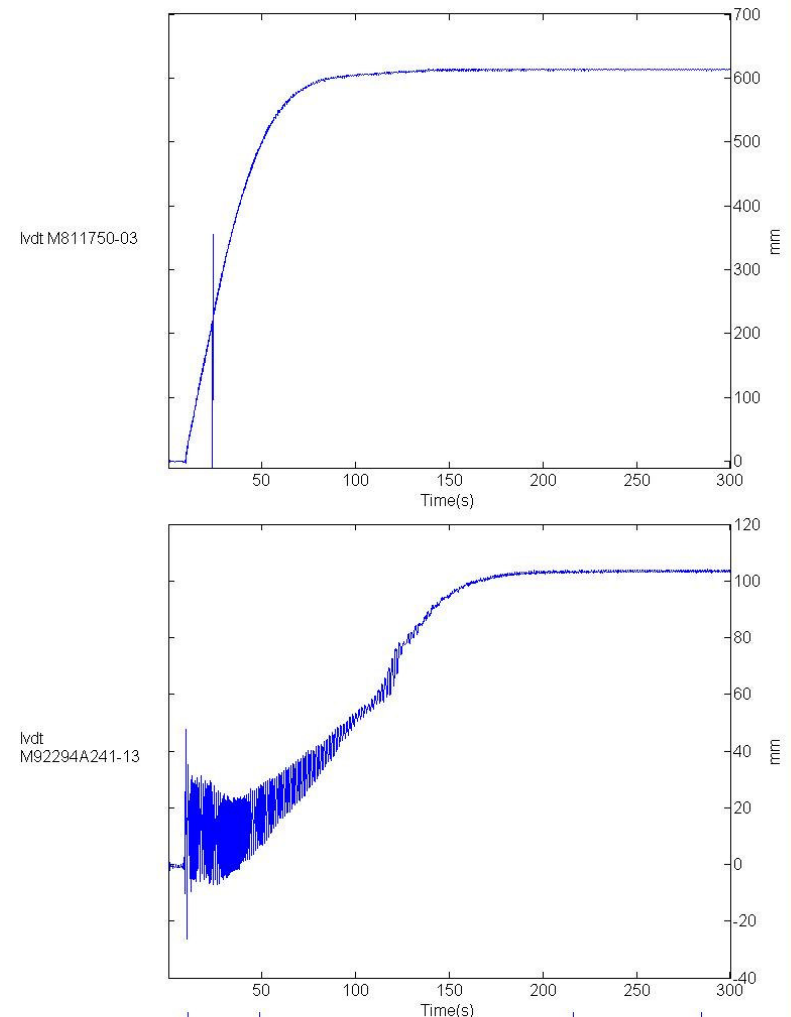
FLIGHT 1

Long-Term Time Records

4

5.14 Centrifuge test MP3, frequency sweep earthquake

Soil surface and structural settlement



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

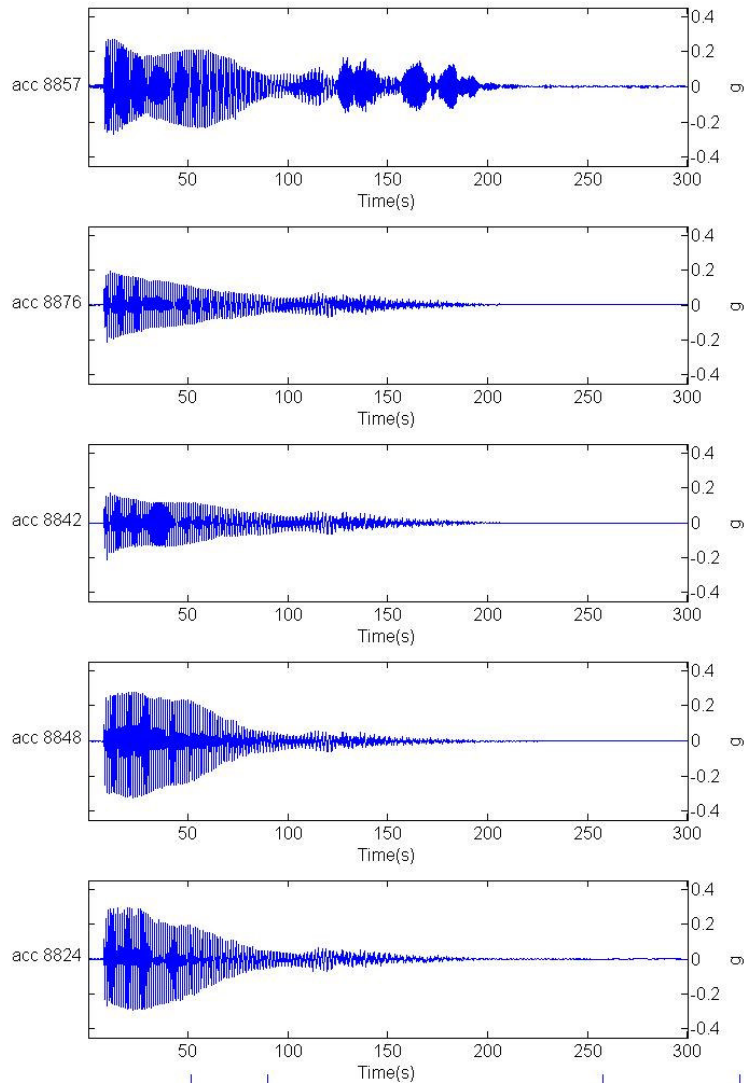
Figure No.

FLIGHT 1

Long-Term Time Records

sweep

Accelerations of structure and soil under structure



TEST MP3

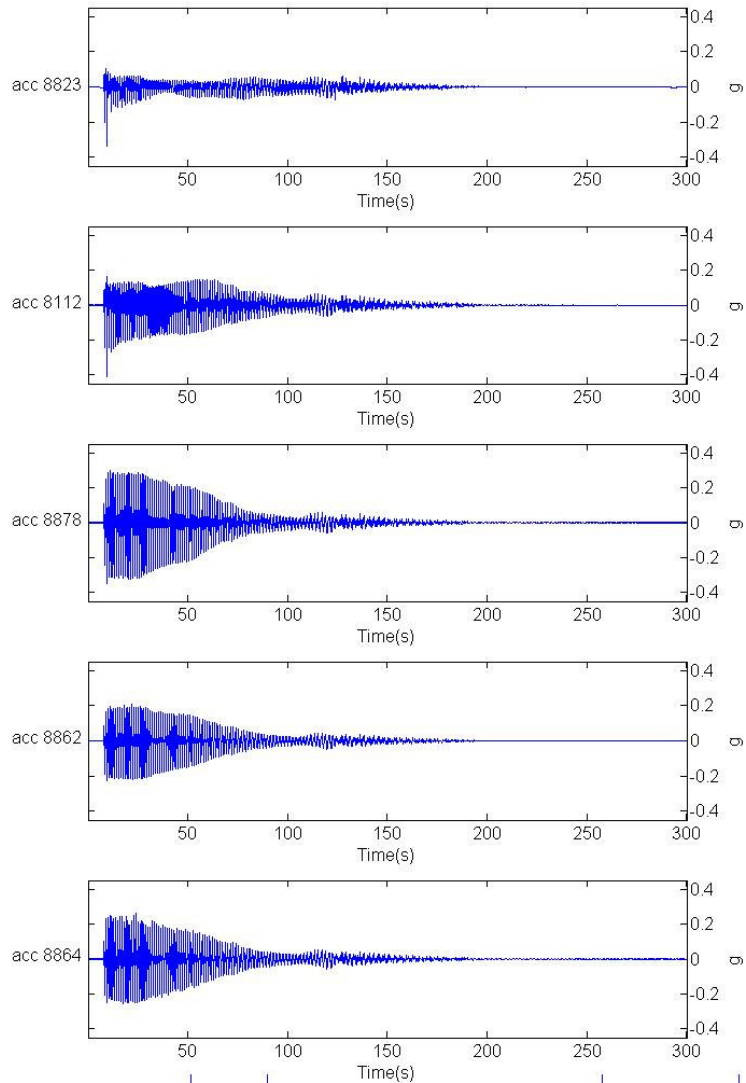
FLIGHT 1

Scales: Prototype
8th order Butterworth Filter at 500Hz
Long-Term Time Records

Earthquake
sweep

Figure No.

Accelerations away from structure and box (input) acceleration



TEST MP3

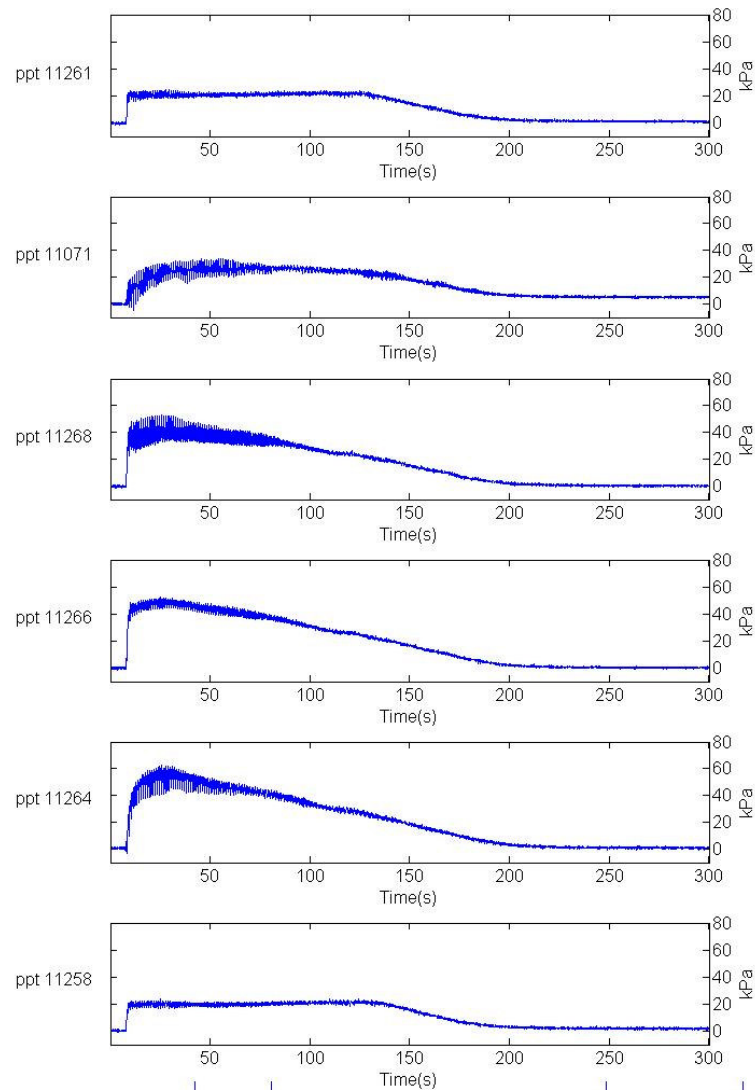
FLIGHT 1

Scales: Prototype
8th order Butterworth Filter at 500Hz
Long-Term Time Records

Earthquake
sweep

Figure No.

Excess pore pressures under structure and between micro-piles



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

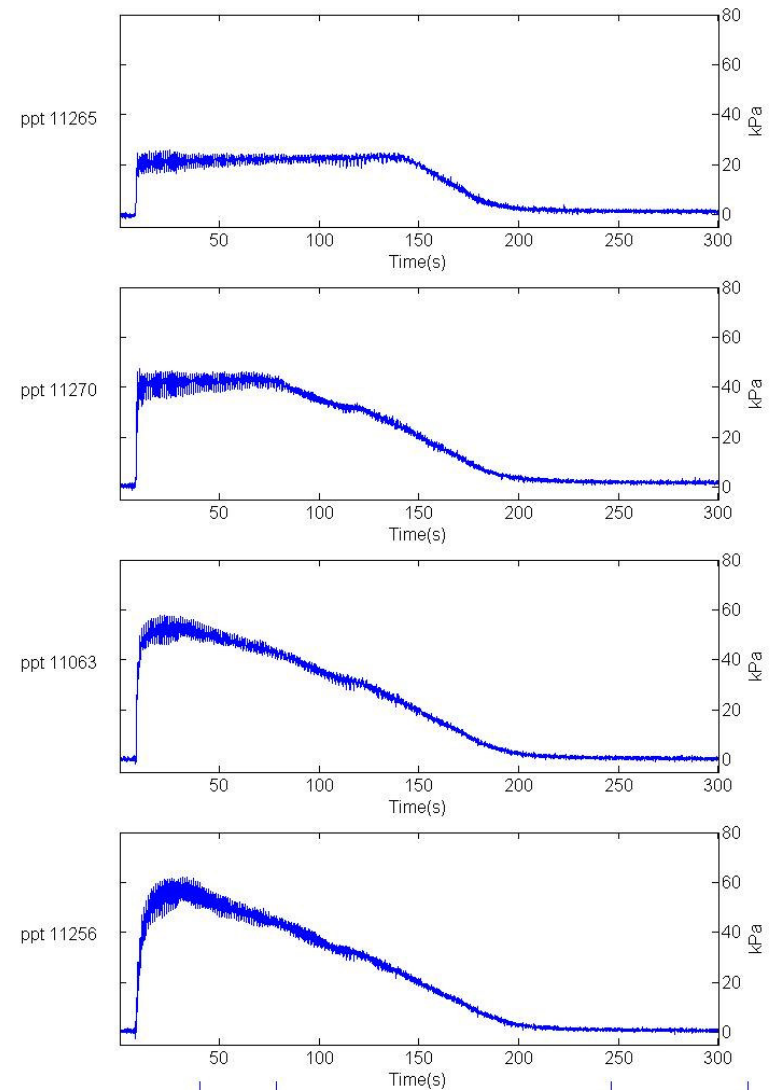
Figure No.

FLIGHT 1

Long-Term Time Records

sweep

Excess pore pressures away from structure



TEST MP3

Scales: Prototype
8th order Butterworth Filter at 500Hz

Earthquake

Figure No.

FLIGHT 1

Long-Term Time Records

sweep