

**Integrity of landfills founded on  
liquefiable foundation - Data report on  
centrifuge tests IT05, IT07 and IT08**

N.I. Thusyanthan<sup>1</sup> & S.P.G. Madabhushi<sup>2</sup>

**CUED/D-SOILS/TR339 (2005)**

---

<sup>1</sup> Research Fellow, Churchill college, University of Cambridge

<sup>2</sup> Senior Lecturer, Engineering Department, University of Cambridge



<b>1</b>	<b>INTRODUCTION.....</b>	<b>4</b>
1.1	MODEL PREPARATION .....	5
1.1.1	<i>Model IT05 .....</i>	5
1.1.2	<i>Model IT07 and Model IT08 .....</i>	7
1.2	MODEL EARTHQUAKES.....	8
<b>2</b>	<b>CENTRIFUGE RESULTS.....</b>	<b>10</b>
2.1	RESULTS FROM TEST IT05 .....	10
2.1.1	<i>Data from IT05, Earthquake 1 .....</i>	10
2.1.2	<i>Data from IT05, Earthquake 2 .....</i>	13
2.1.3	<i>Data from IT05, Earthquake 3 .....</i>	16
2.1.4	<i>Data from IT05, Earthquake 4 .....</i>	19
2.1.5	<i>Data from IT05, Earthquake 5 .....</i>	22
2.1.6	<i>Data from IT05, Earthquake 6 .....</i>	25
2.2	RESULTS FROM TEST IT07 .....	28
2.2.1	<i>IT07, Earthquake1.....</i>	28
2.2.2	<i>IT07, Earthquake 2.....</i>	32
2.3	RESULTS FROM TEST IT08.....	36
2.3.1	<i>IT08, Earthquake 1.....</i>	36
2.3.2	<i>IT08, Earthquake 2.....</i>	39
2.3.3	<i>IT08, Earthquake 3.....</i>	43

## 1 Introduction

The possibility of ground water contamination by leachate escaping from a landfill is one of the main concerns associated with the liner failures of landfills. Landfill design legislations usually specify a minimum height between the base liner and the ground water level. However more recently, landfills have been allowed to be designed below ground water level (Dunn and De, 2003). There are many potential benefits in such design. One of the main supportive arguments and environmental benefits of such a design is that the hydraulic gradient is towards the landfill, hence any liner breach would result in water getting into the landfill rather than leachate migrating out into the ground where it could pollute the ground water. The cost benefits come in two forms. Firstly, the capacity of the landfill is increased by excavating further below ground for the same land area. Secondly, the excavated soil could be used as the daily cover resulting in huge savings as ‘above-ground’ landfills require daily cover which usually has to be transported to the landfill site. An example of a landfill below ground water level is the Virginia landfill (Southeastern Public Service Authority-SPSA landfill's fifth cell) which was designed and built successfully below ground water level. The ‘below-ground’ design increased the landfill capacity by 60% and saved \$10 million on the transportation of daily cover soil. The SPSA's cell design was awarded the Silver Spring, Md.-based Solid Waste Association of North America's (SWANA) Gold Award in landfill management.

For landfills located in seismic regions and below ground water level, the risk of earthquake damage is particularly high above a potentially liquefiable foundation. Earthquake loading, causing liquefaction or weakening of the foundation, could induce major liner damage due to movement of the side liner and settlement of the base liner. Such liner damage is difficult to detect for a completed landfill. Thus understanding the effects of an earthquake on landfills founded on liquefiable foundation is important.

This chapter presents results from dynamic centrifuge tests on three difference MSW landfill models representing different field conditions and discusses the implications of the results. The performance and integrity of landfills founded on liquefiable foundations was studied by carrying out dynamic centrifuge testing on 3 different landfill models (IT05, IT07 & IT08), each representing a different field scenario. The pore fluid was generally kept at 20 mm below

soil surface in all the models. For 50g tests, this represents a ground water table of 1 m below ground surface at prototype scale.

This report provides the data obtained from the centrifuge tests. Further details and analysis of the results are given in Thusyanthan 2005, Ph.D thesis, University of Cambridge.

## 1.1 Model preparation

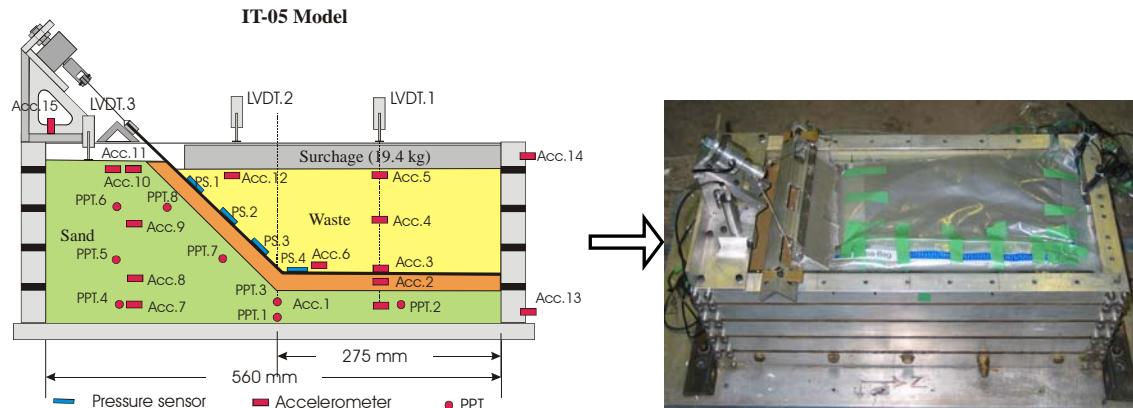
All three models (IT05, IT07 & IT08) were prepared as described in section 3.7.1. More detailed preparation methods specific to each model are described below. Cross sections of the models are shown in Fig. 1.1.

### 1.1.1 Model IT05

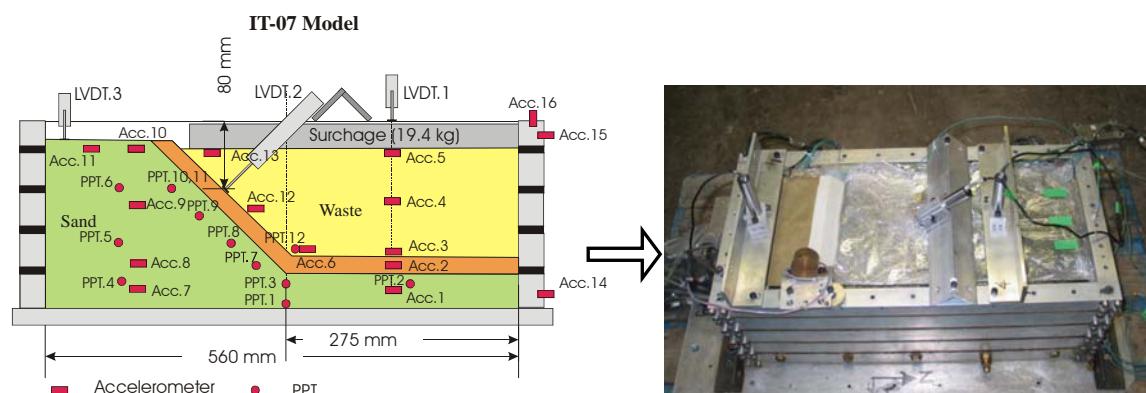
Fig. 1.1(a) shows the cross section of the centrifuge model IT05. The model IT05 represents a completed MSW landfill with a geomembrane/clay liner system founded on a liquefiable foundation.

The initial stages of model preparation of model IT05 was similar to that reported in Chapter 3 (section 3.7.1- Thusyanthan 2005). After the completion of sand pluviation the model was saturated with water. The water was then drained under gravity to enable the slope excavation. The clay liner strips were carefully placed into the landfill side slope and the base. In order to prevent the pore fluid from getting into the model waste during re-saturation and test, a silica rubber sealant was used to seal the gap between the clay liner and the ESB side walls. This seal was flexible enough to allow relative movement of clay liner and the side wall while providing a good seal against fluid flow. The model geomembrane was placed on the clay liner and fixed to the load cell. Model waste was then placed inside the landfill in layers and compressed. Accelerometers were placed as shown in Fig. 1.1(a). In order for the landfill base to experience normal stresses similar to that from a 15 m high waste fill, 19.4 kg of lead shot was used as a surcharge on top on the landfill model. The surcharge of 19.4 kg on the model provides an overburden vertical stress of 108 kPa which along with the 44 kPa stress from the model waste would exhibit a total stress of 152 kPa at the clay liner base. This could represent a MSW fill height of 15m with density  $10 \text{ kN/m}^3$ .

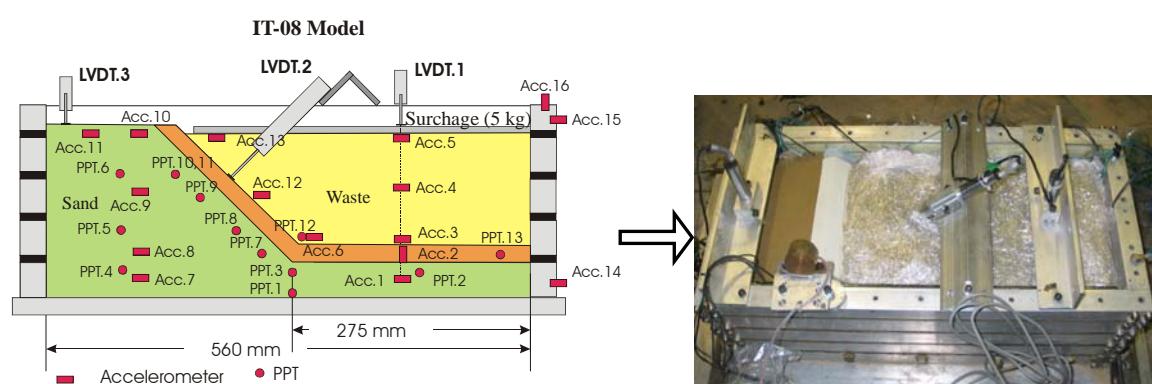
The completed model was re-saturated with methylcellulose (75 cSt). Since there was already water in the model from initial saturation, the viscosity of resulting pore fluid in model could not be stated precisely. The pore fluid in the model was drained after the test and the viscosity was measured to be 10 cSt. However this viscosity may not be uniform in the model.



**Fig. 1.1 (a) Schematic cross section and actual centrifuge model IT05**



**Fig. 1.1 (b) Schematic cross section and actual centrifuge model IT07**



**Fig. 1.1 (c) Schematic cross section and actual centrifuge model IT08**

**Fig. 1.1 Schematic cross section of centrifuge model**

### *1.1.2 Model IT07 and Model IT08*

The models IT07 and IT08 represent a completed MSW landfill and an active MSW landfill respectively. Both models represent landfills with a single clay liner system. The model preparation of IT07 and IT08 was similar to that of IT05 except for the fact they were initially saturated with methylcellulose as opposed to with water in IT05. Models IT07 and IT08 were saturated with methylcellulose (50 cSt) after the sand pluviation stage. The models were then allowed to drain under gravity. However there was not much drainage as the methylcellulose was viscous. Therefore a vacuum had to be applied to the model through the drainage holes located at the base of the model to enable the excavation of the side slope for the model. Once the excavation was done to the required depth, the clay liners were placed on the base and the side slope. The model waste was then placed in layers and compressed to obtain uniform density of 9 kN/m<sup>3</sup>. A LVDT was fixed perpendicular to the side clay liner to measure the below ground movement of clay liner. The LVDT measures the movement of the side clay liner at a prototype depth of 3m below ground. A bag full of lead shot of the required weight (19.4 kg in IT07, 5 kg in IT08) was placed uniformly on top of the model waste to produce the required overburden stress. The completed model was finally re-saturated with methycellulose up to a level 40 mm below the sand surface.

Model IT07 had the same surcharge as IT05, thus it represented a completed landfill with 15 m of waste fill. Model IT08 had a surcharge of 5 kg, which provides an overburden stress of 28 kPa at 50g. This overburden was chosen so that the model would represent an active landfill, with 7m waste height, whose normal stress is just above the buoyancy force of water (i.e there is a high chance of heave due to excess pore pressure from earthquake loading). Table 1.1 provides a summary of the overburden stresses and the total stress on the base clay liner at 50g. Table 1.2 provides the details of vertical downwards force and upthrust force in model IT08.

In order to observe the clay liner and the top soil surface during the test a small video camera was mounted on the side wall of the ESB container. The video from this camera was recorded throughout the test.

**Table 1.1 Overburden stresses and the total stresses at the liner base in the model at 50g.**

Model	Normal stress in liner base from model waste (kPa)	Overburden stress (kPa)	Total stress at the base of landfill (i.e above the clay liner) (kPa)
IT07	44	108	152
IT08	44	28	72

**Table 1.2 Up thrust and total vertical stress in Model IT08 at 1g and 50g.**

		At 1g	At 50g
a.	volume of water displaced $0.235 \times (0.295 \times 0.14 + 0.5 \times 0.16 \times 0.14)$	0.0123 m <sup>3</sup>	0.0123 m <sup>3</sup>
b.	Up-thrust (water mass displaced)	12.34 kg	616.88 kg
c.	Up-thrust force	0.12 kN	6.05 kN
d.	mass of waste	7.22 kg	361.00 kg
e.	mass of surcharge (IT07, IT08)	19.4, 5.00 kg	250.00, 970.00 kg
f.	mass of clay liner	3.64 kg	182.00 kg
<b>Model IT07</b>			
g.	Total mass (clay liners + waste + surcharge)	30.26 kg	1513.00 kg
h.	Vertical force downwards	0.30 kN	14.84 kN
i.	Net force downwards (h-c)	0.18 kN	8.79 kN
<b>Model IT08</b>			
j.	Total mass (clay liners + waste + surcharge)	15.86 kg	793.00 kg
k.	Vertical force downwards	0.16 kN	7.78 kN
l.	Net force downwards (k-c)	0.04 kN	1.73 kN

## 1.2 Model earthquakes

The following tables provide the details of the simulated earthquakes applied to each of the models. Ample time was allowed between each of the model earthquakes in order to allow and record full excess pore pressure dissipation and settlements.

**Table 1.3 Simulated earthquake loadings in test IT05, prototype scale [model scale].**

Model earthquake number	Driving frequency (Hz)	Duration (s)	Maximum base acceleration-Acc.1(g)
E.1	0.6 [30]	15[0.3]	0.068 [3.410]
E.2	0.8 [40]	15[0.3]	0.131 [6.554]
E.3	1 [50]	15[0.3]	0.184 [9.191]
E.4	1 [50]	15[0.3]	0.202 [10.111]
E.5	1 [50]	15[0.3]	0.229 [11.47]
E.6	1 [50]	15[0.3]	0.246 [12.29]

**Table 1.4 Simulated earthquake loadings in test IT07, prototype scale [model scale].**

Model earthquake number	Driving frequency (Hz)	Duration (s)	Maximum base acceleration-Acc.1(g)
E.1	1 [50]	15 [0.3]	0.163 [8.15]
E.2	1 [50]	15 [0.3]	0.249 [12.45]

**Table 1.5 Simulated earthquake loadings in test IT08, prototype scale [model scale].**

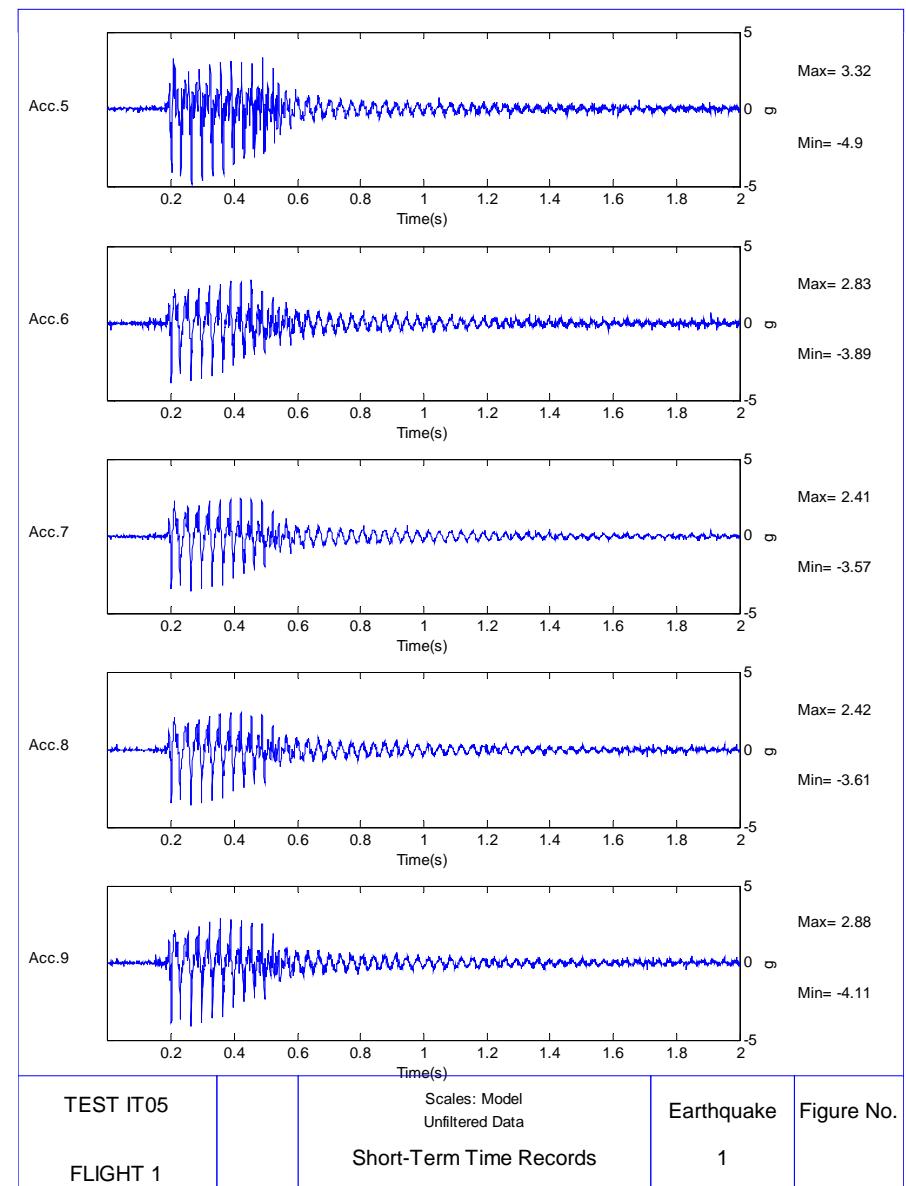
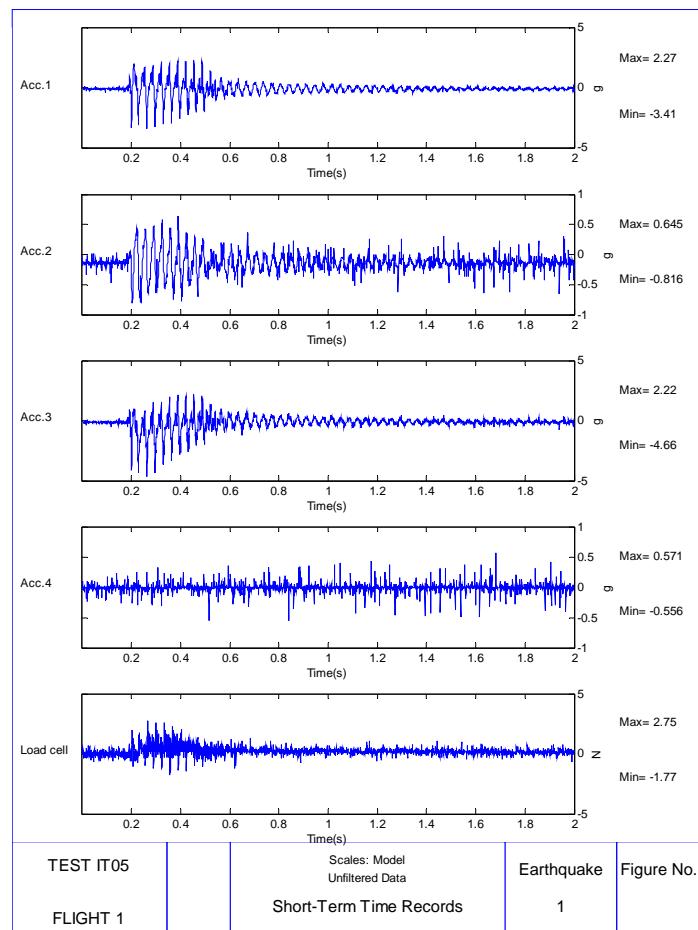
Model earthquake number	Driving frequency (Hz)	Duration (s)	Maximum base acceleration-Acc.1(g)
E.1	1 [50]	15 [0.3]	0.222 [11.09]
E.2	1 [50]	15 [0.3]	0.368 [18.42]
E.3	1 [50]	25 [0.5]	0.350 [17.48]

All the data in the following section is presented at model scale except when stated otherwise.  
A complete set of the data is given in below.

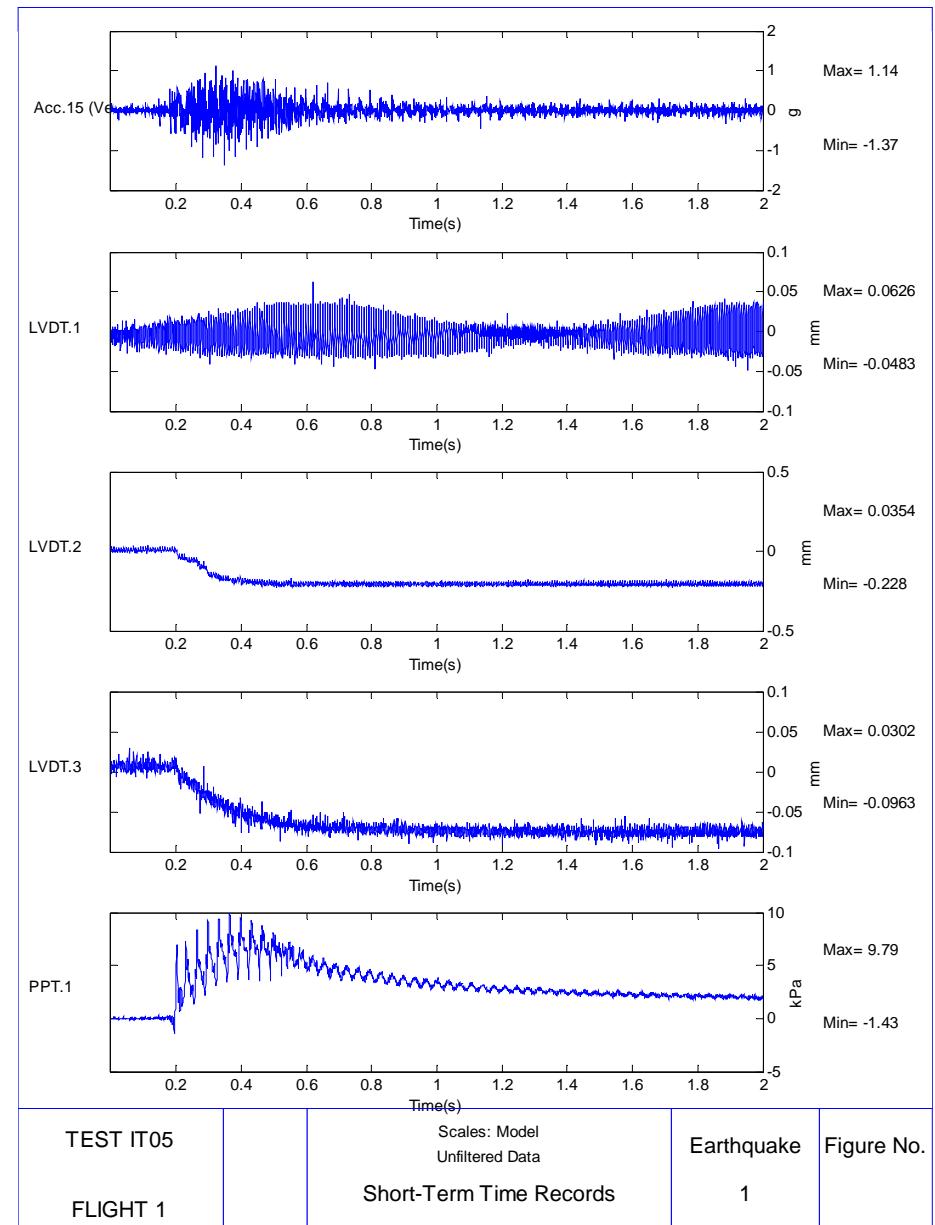
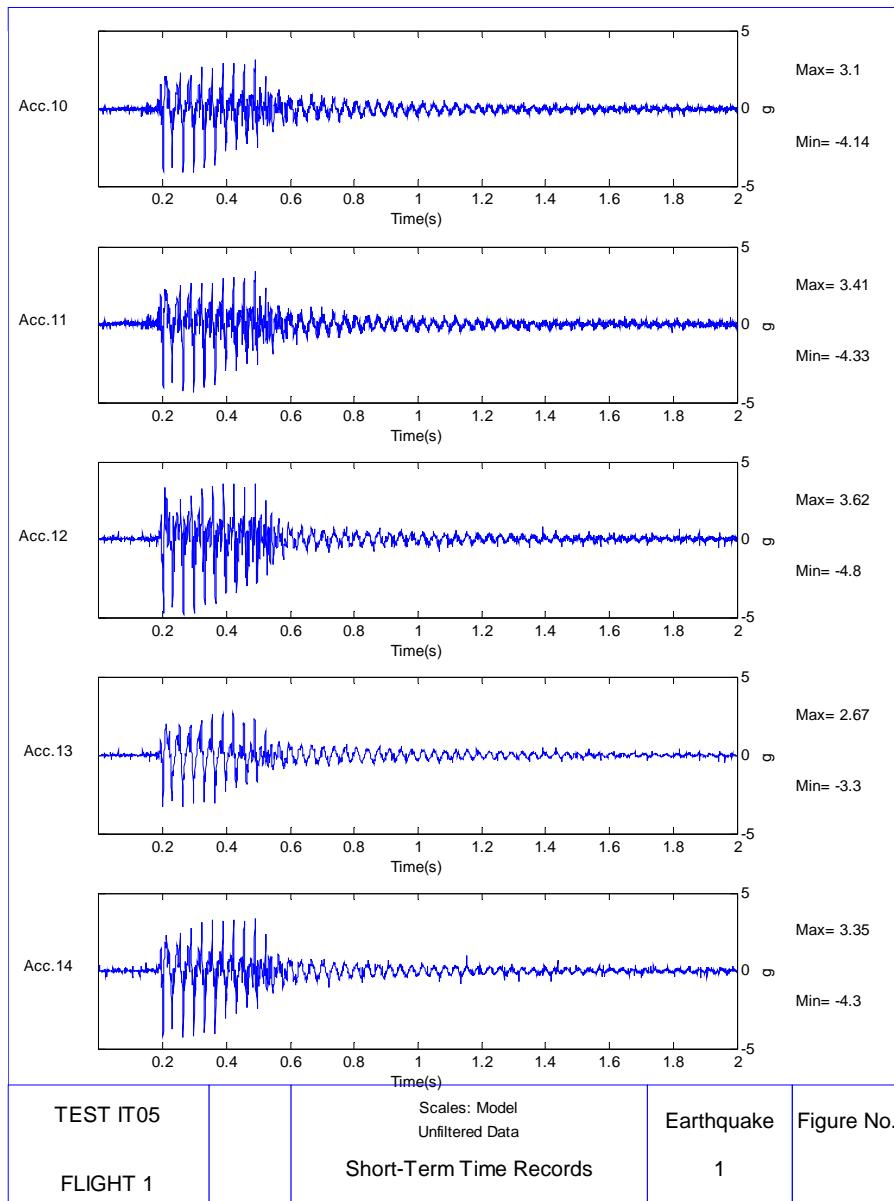
## 2 Centrifuge Results

### 2.1 Results from test IT05

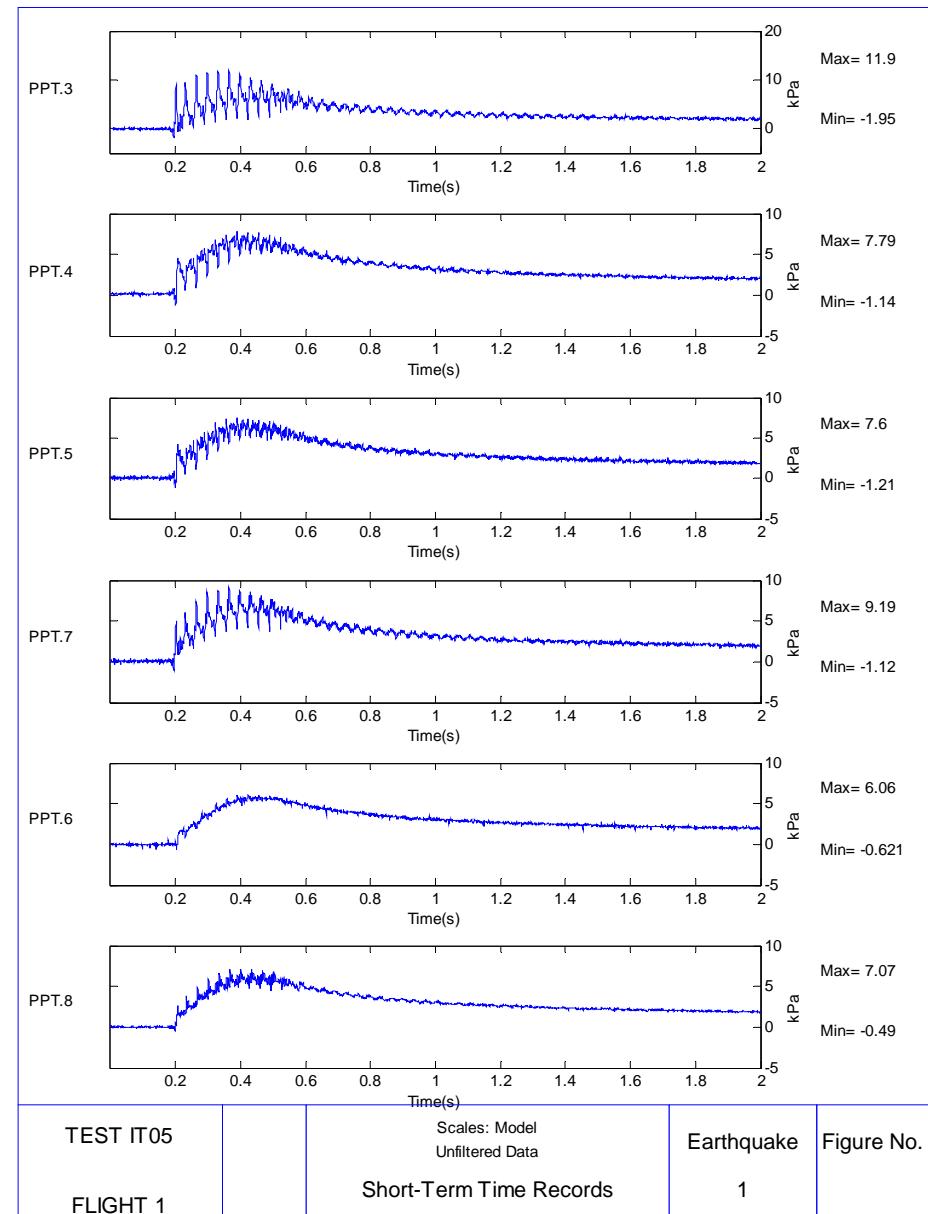
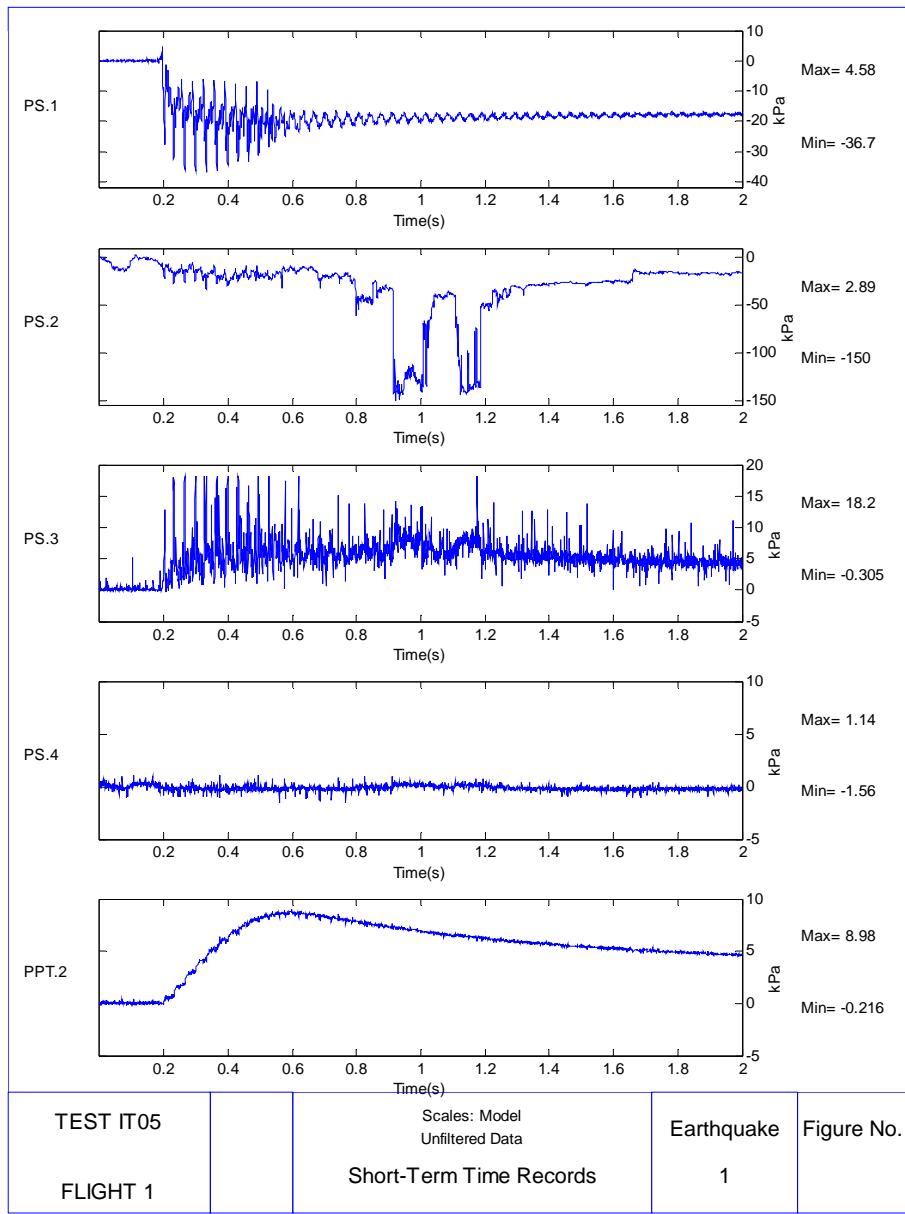
#### 2.1.1 Data from IT05, Earthquake 1



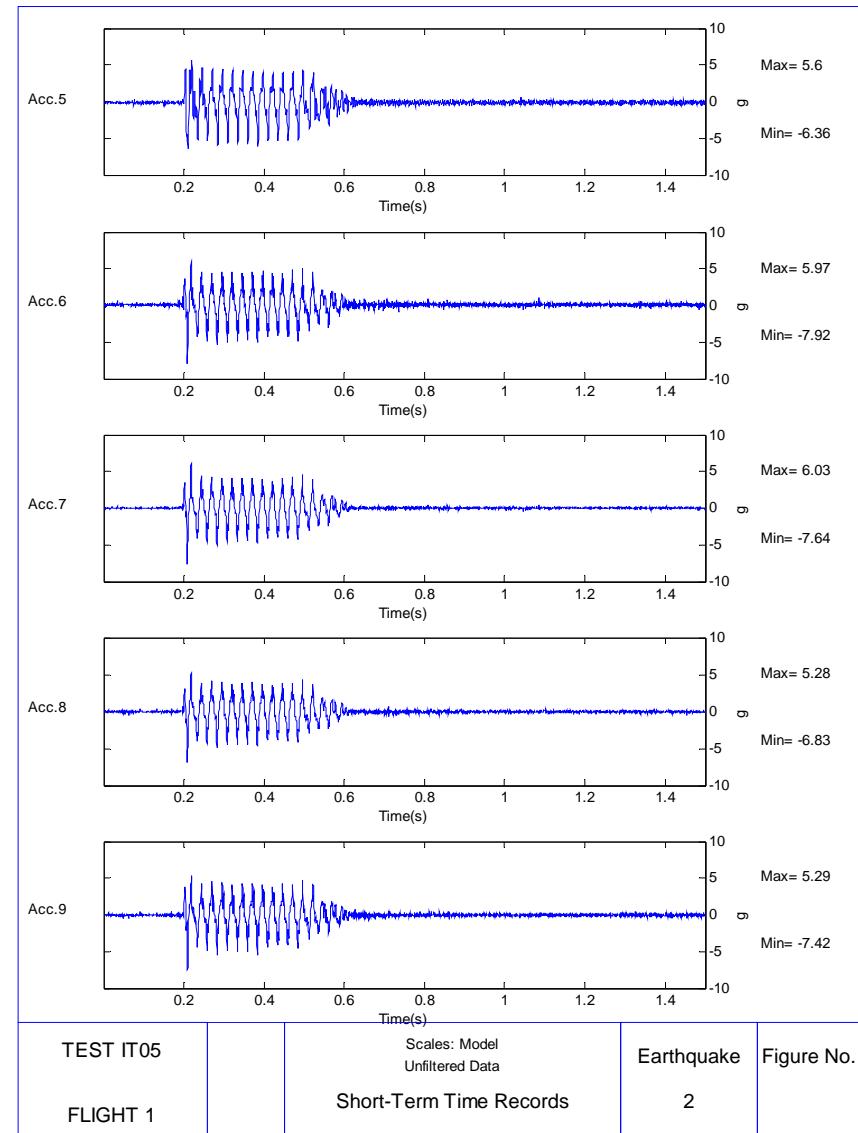
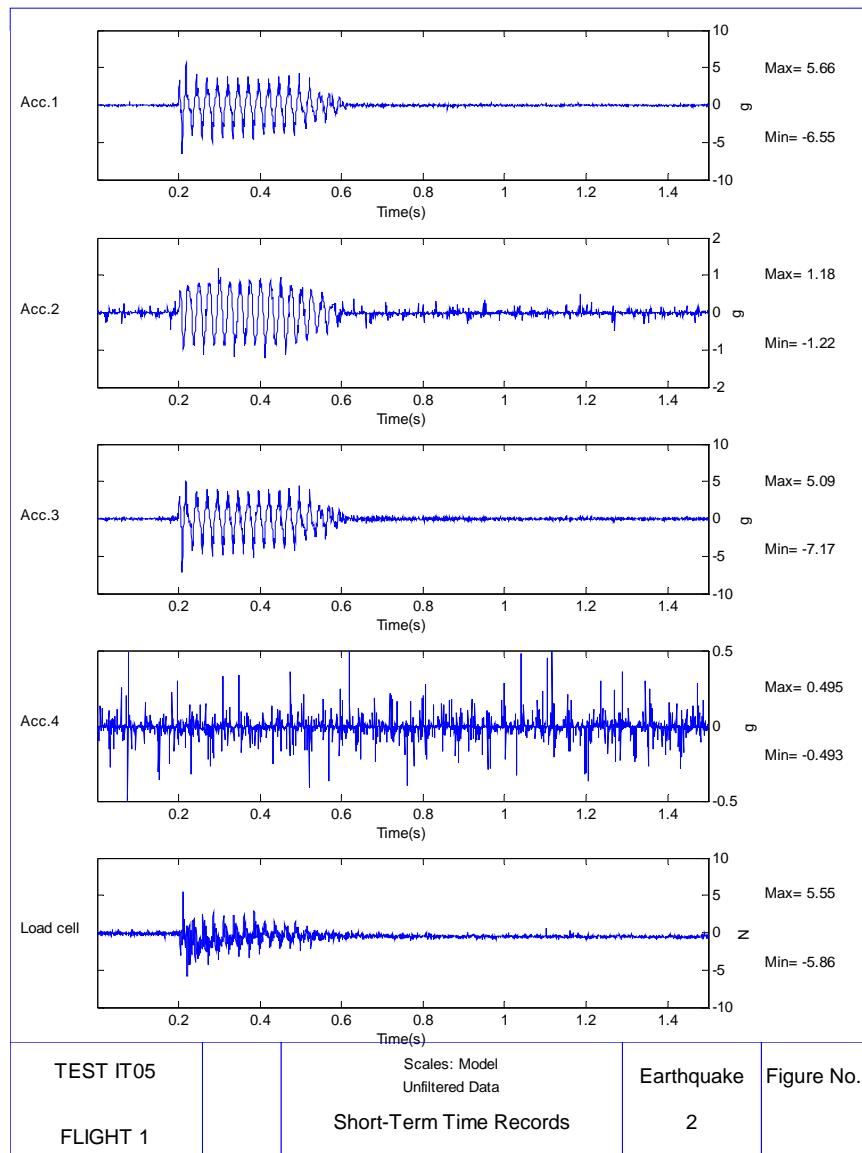
# CUED/D-SOILS/TR339



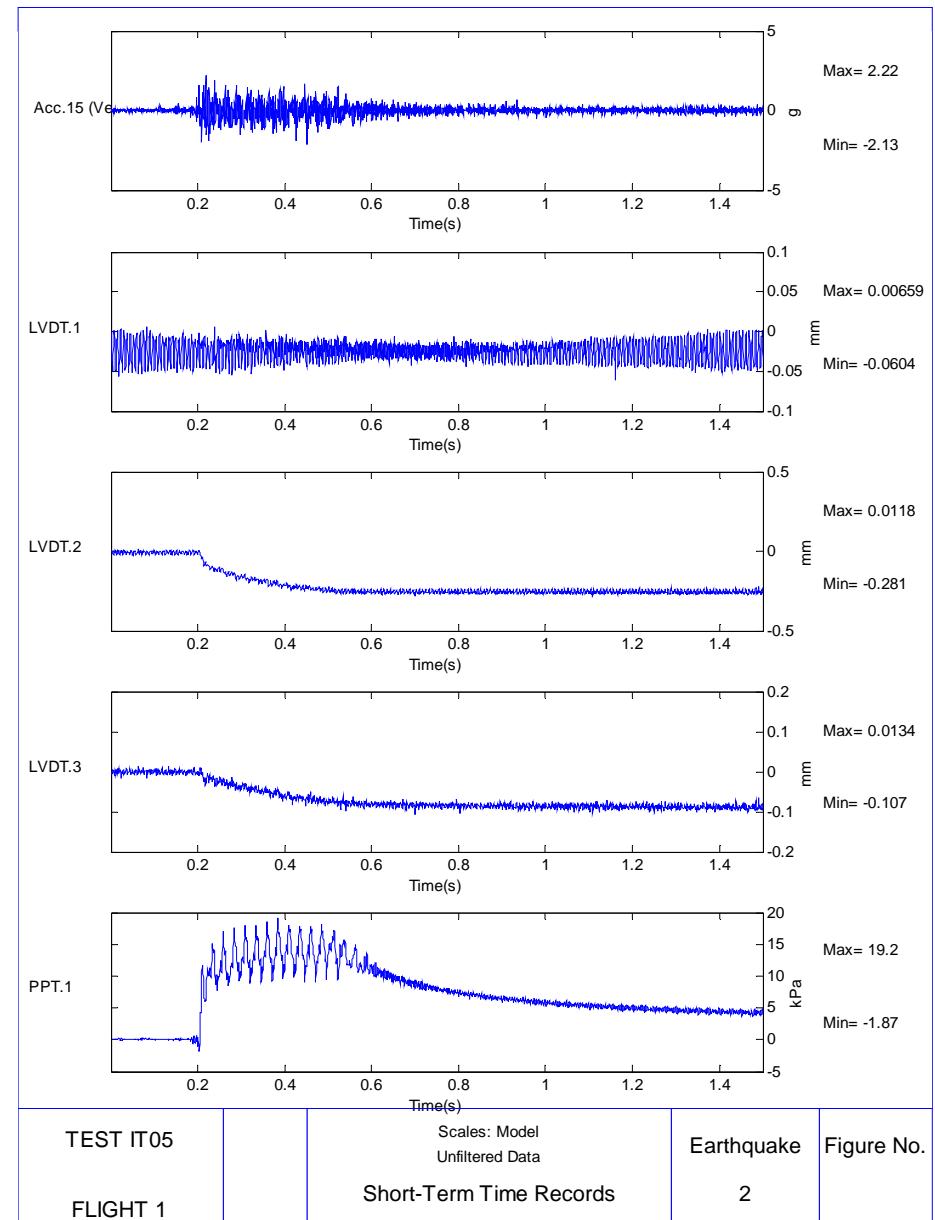
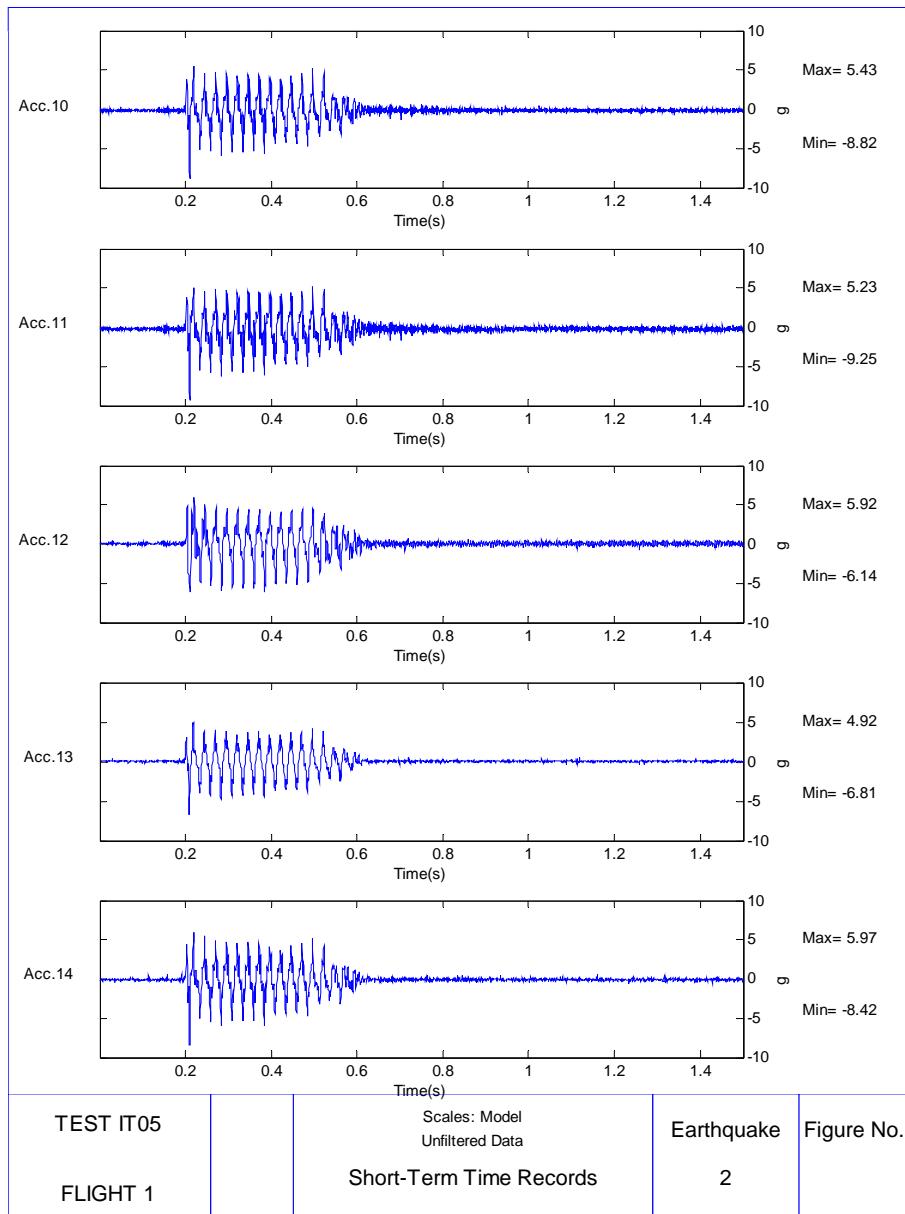
# CUED/D-SOILS/TR339



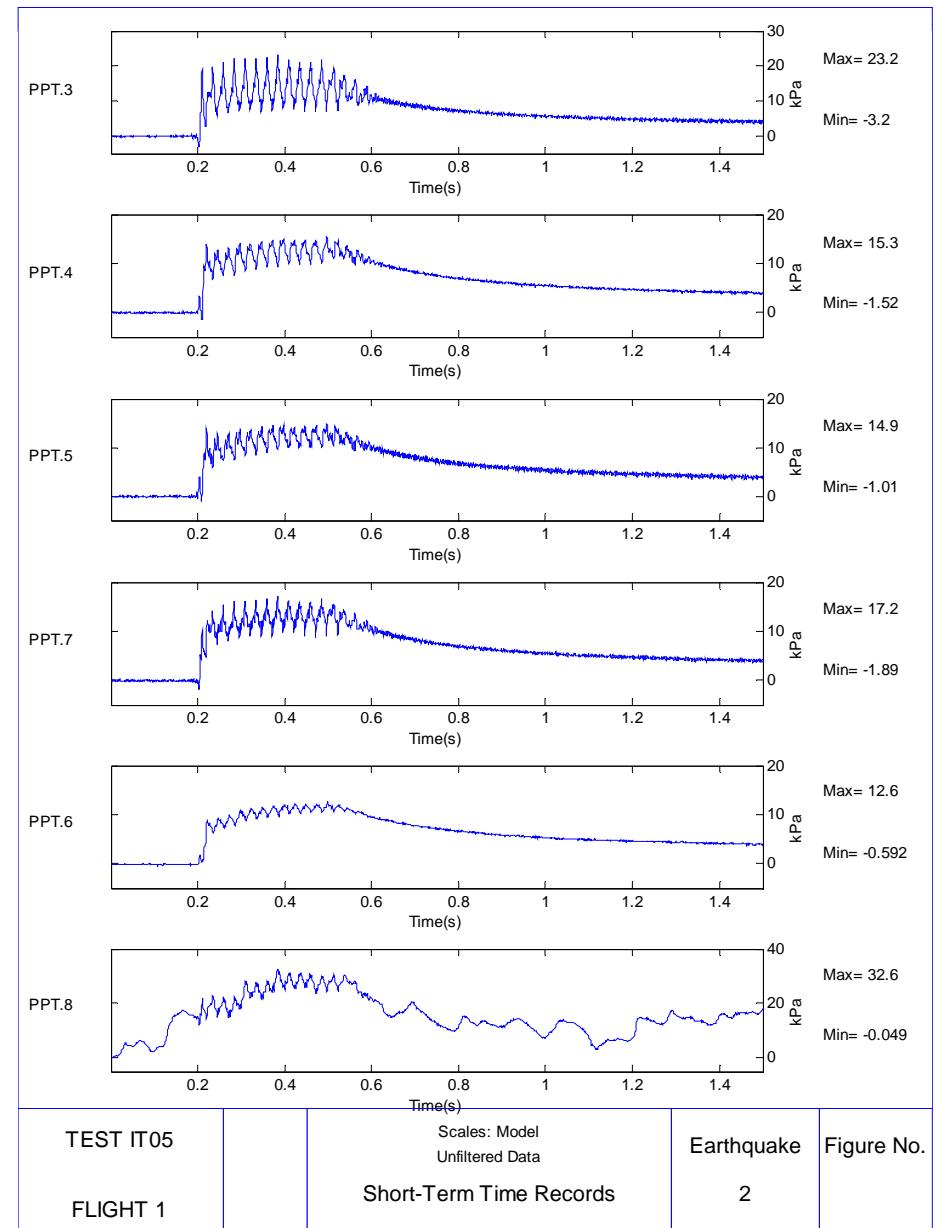
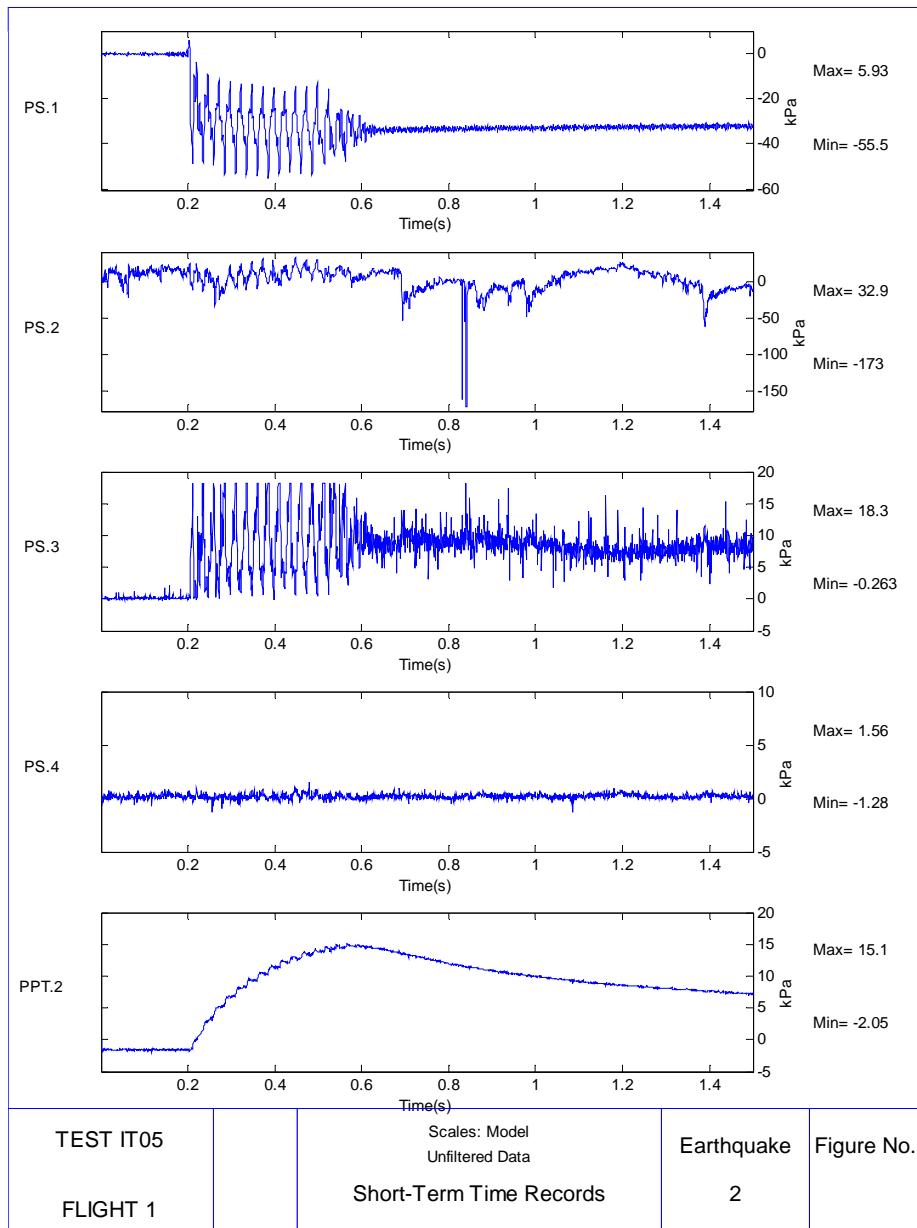
### 2.1.2 Data from IT05, Earthquake 2



# CUED/D-SOILS/TR339

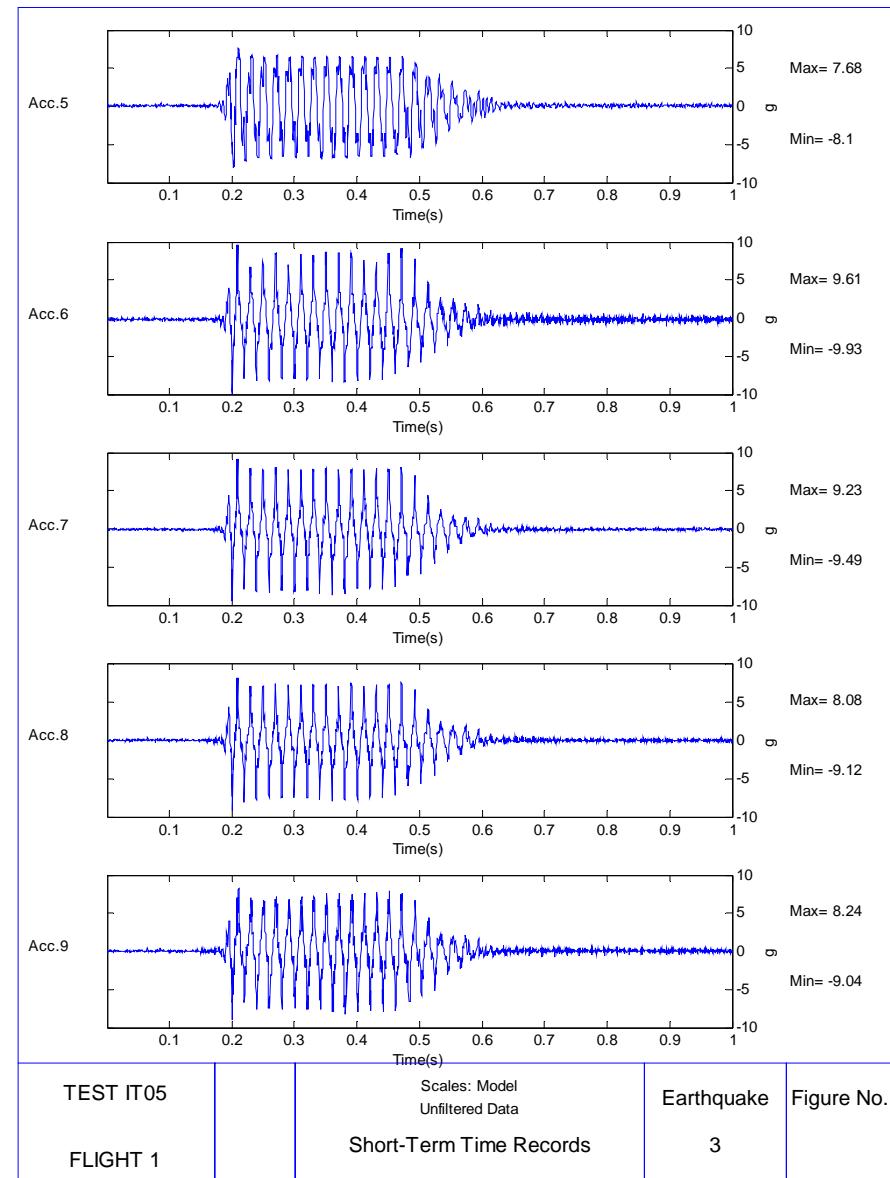
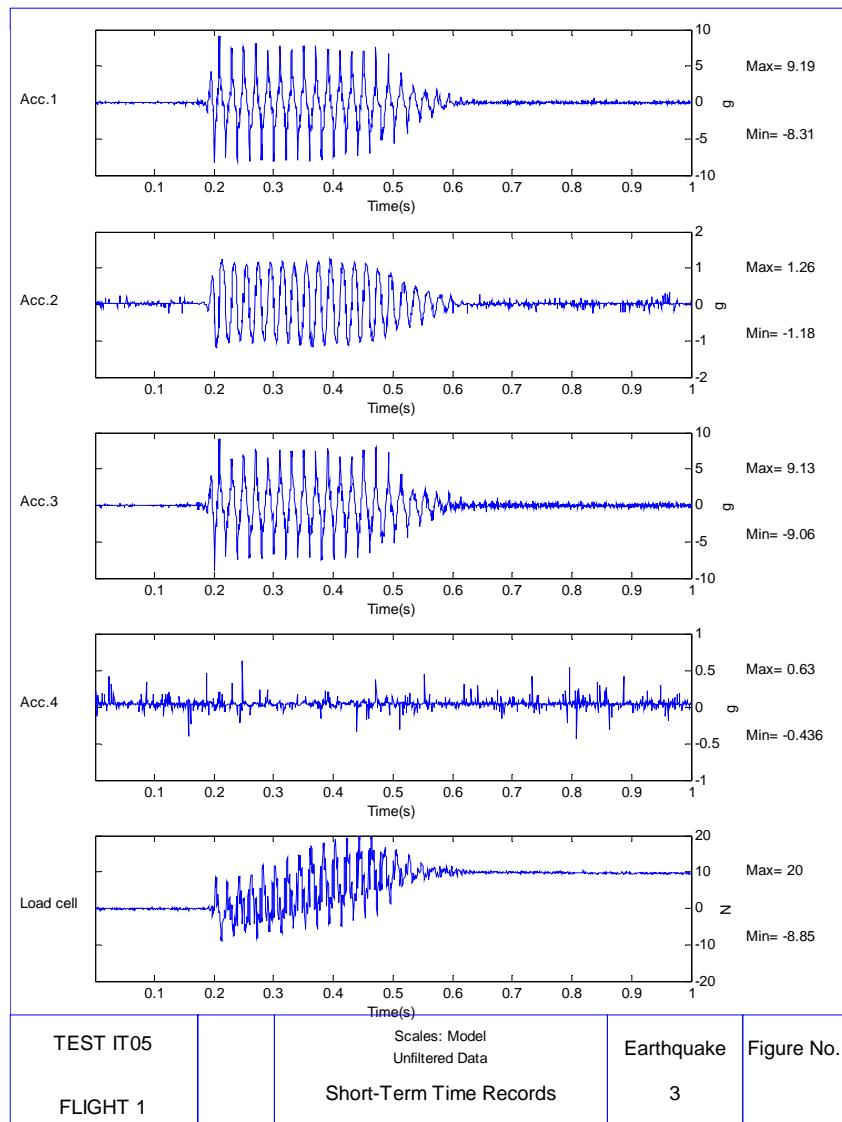


# CUED/D-SOILS/TR339

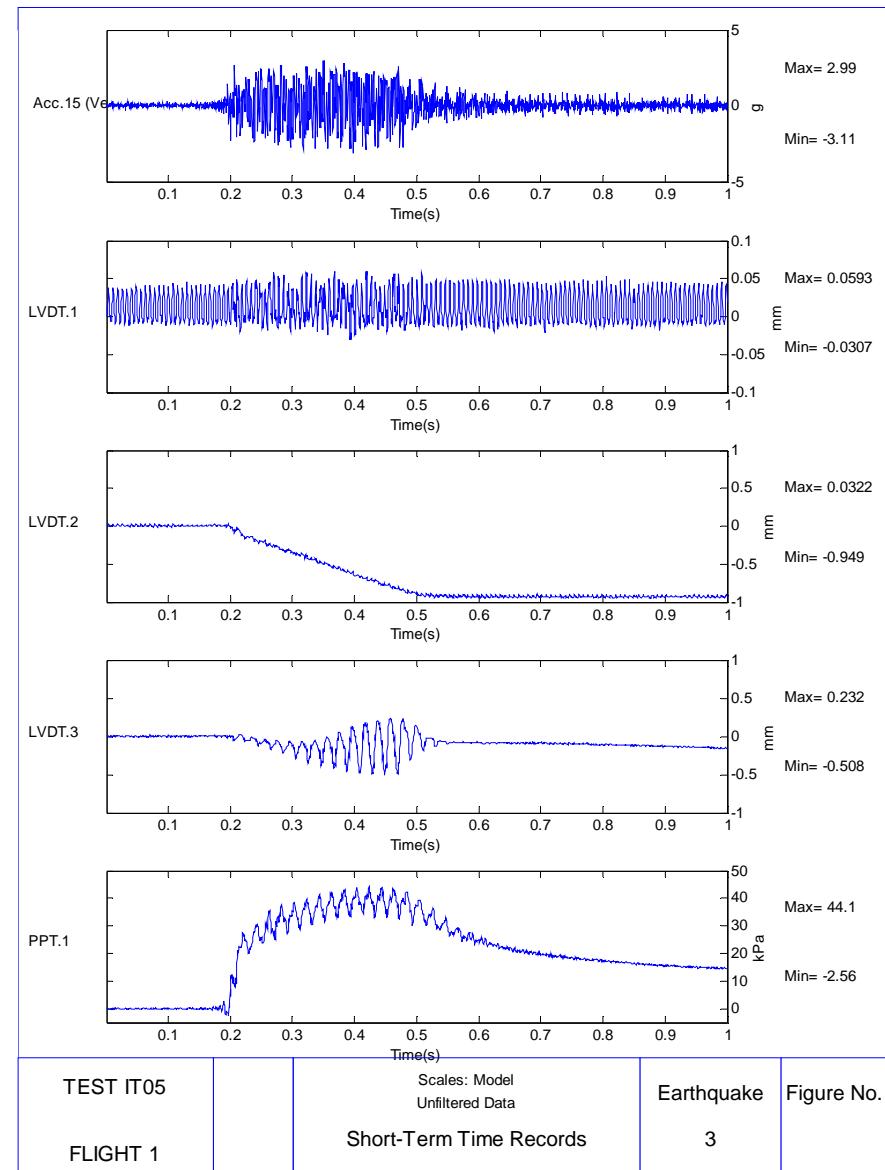
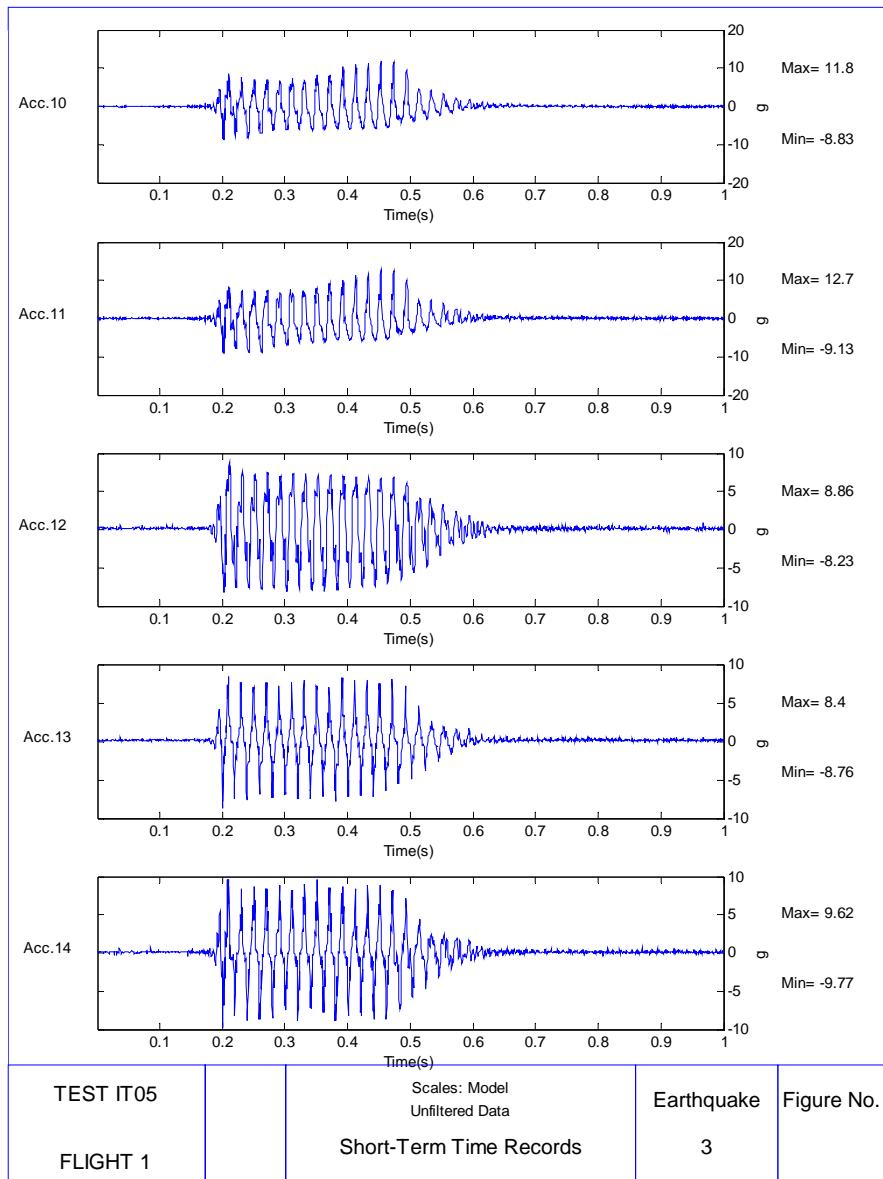


CUED/D-SOILS/TR339

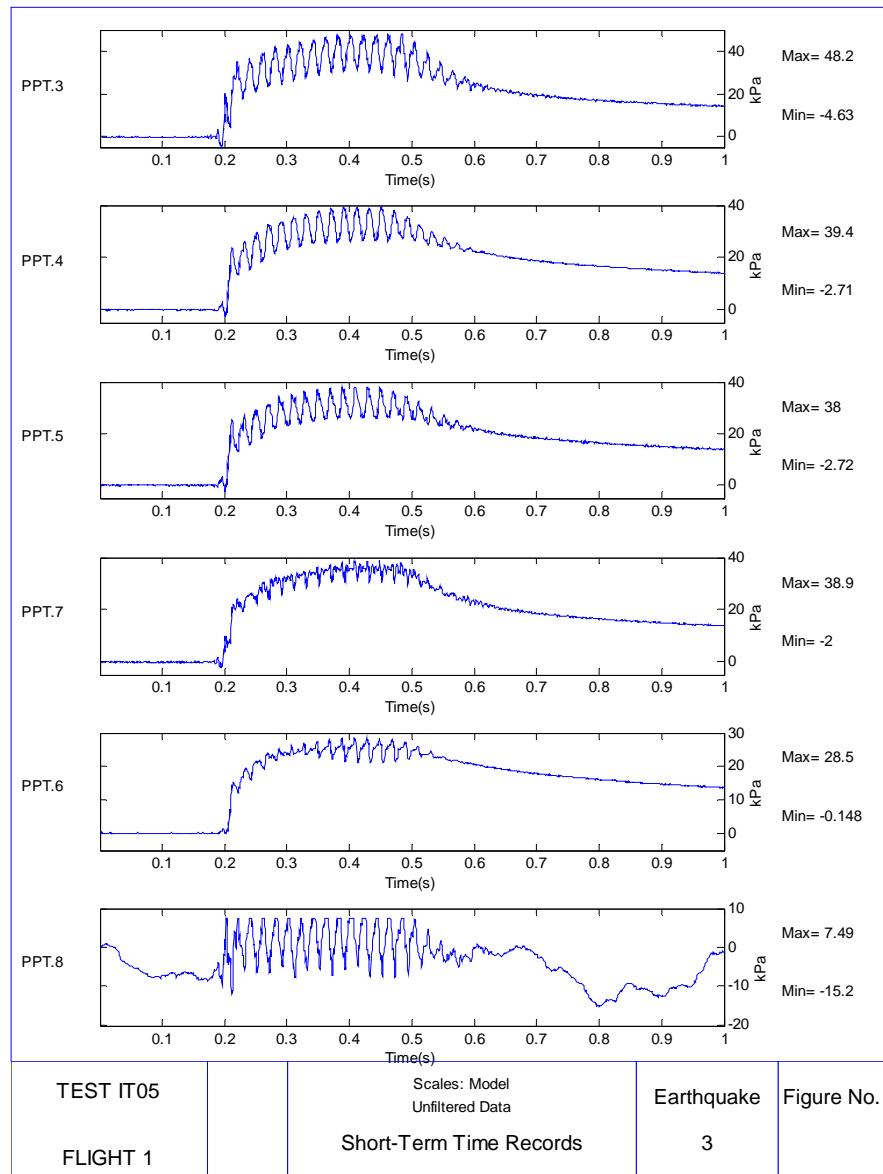
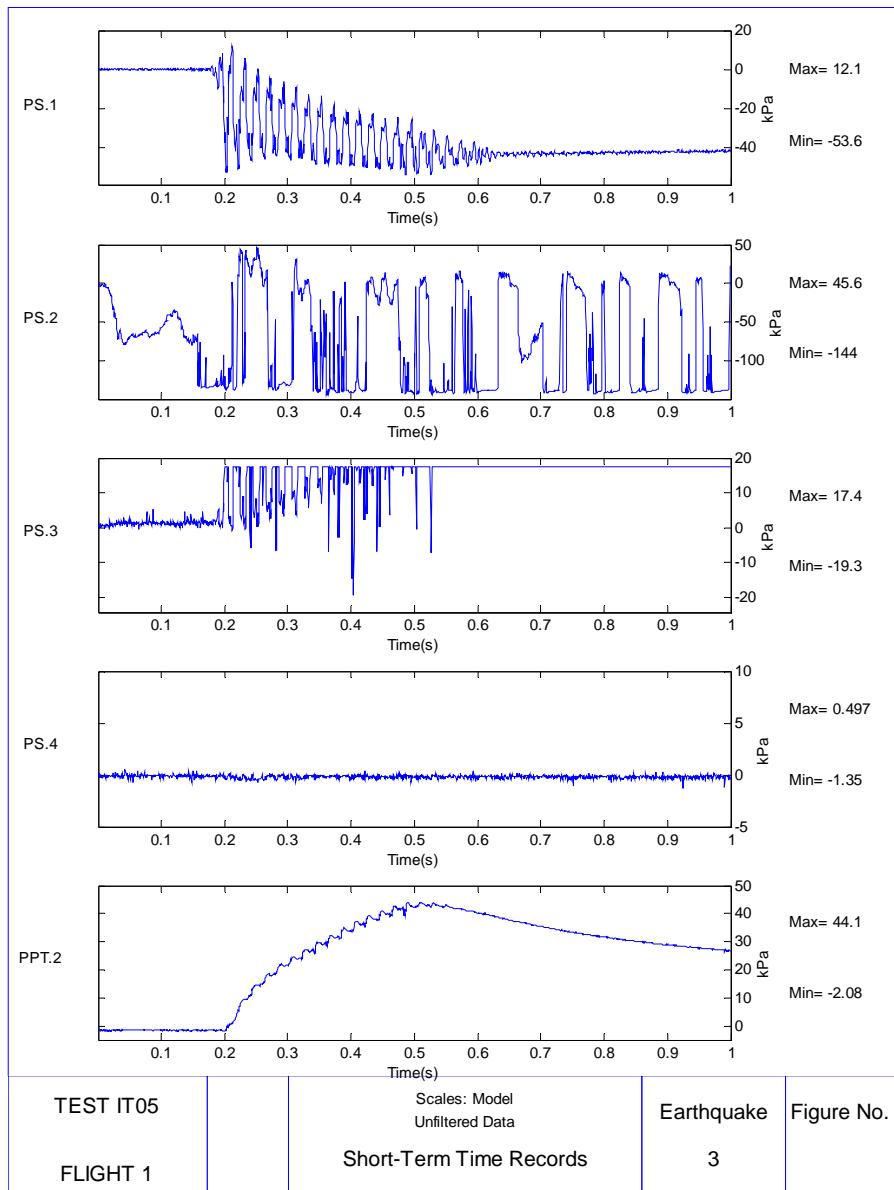
### 2.1.3 Data from IT05, Earthquake 3



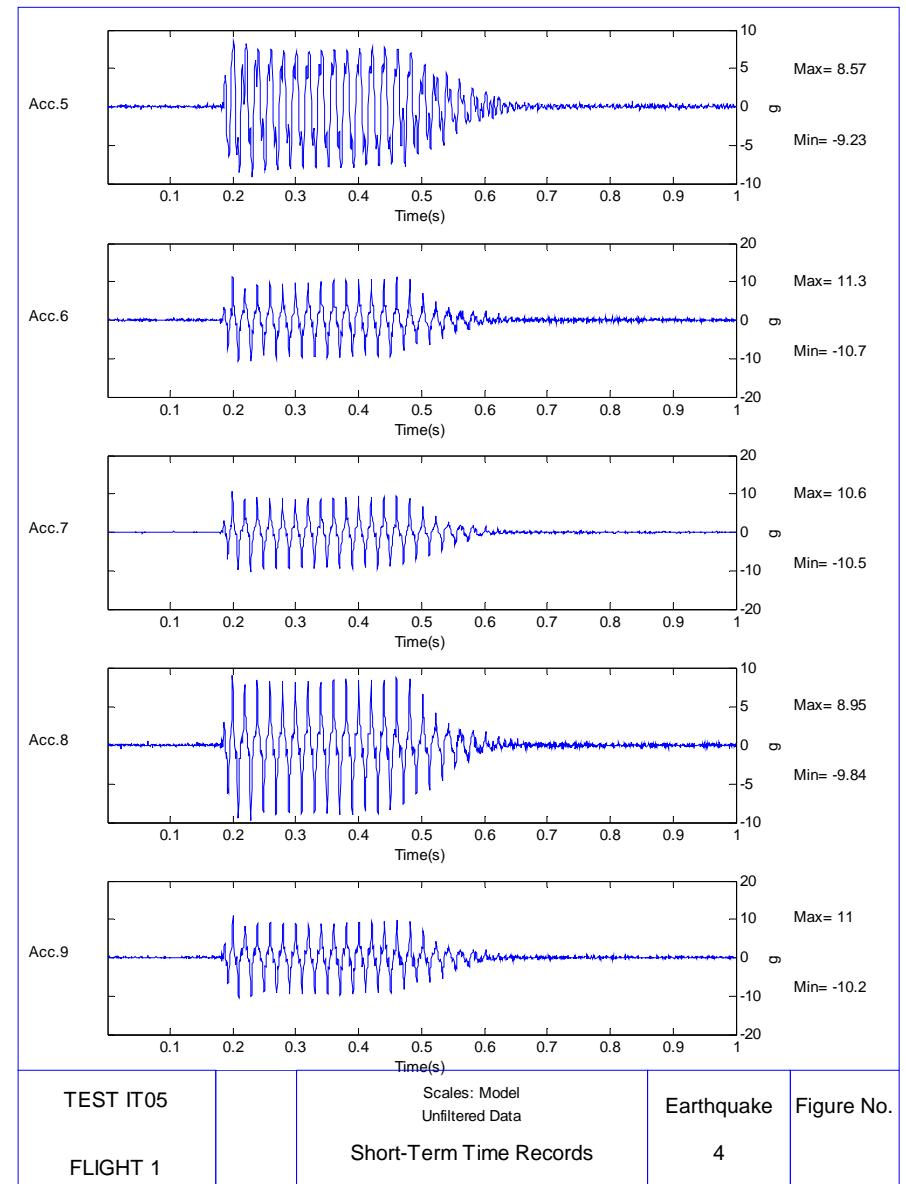
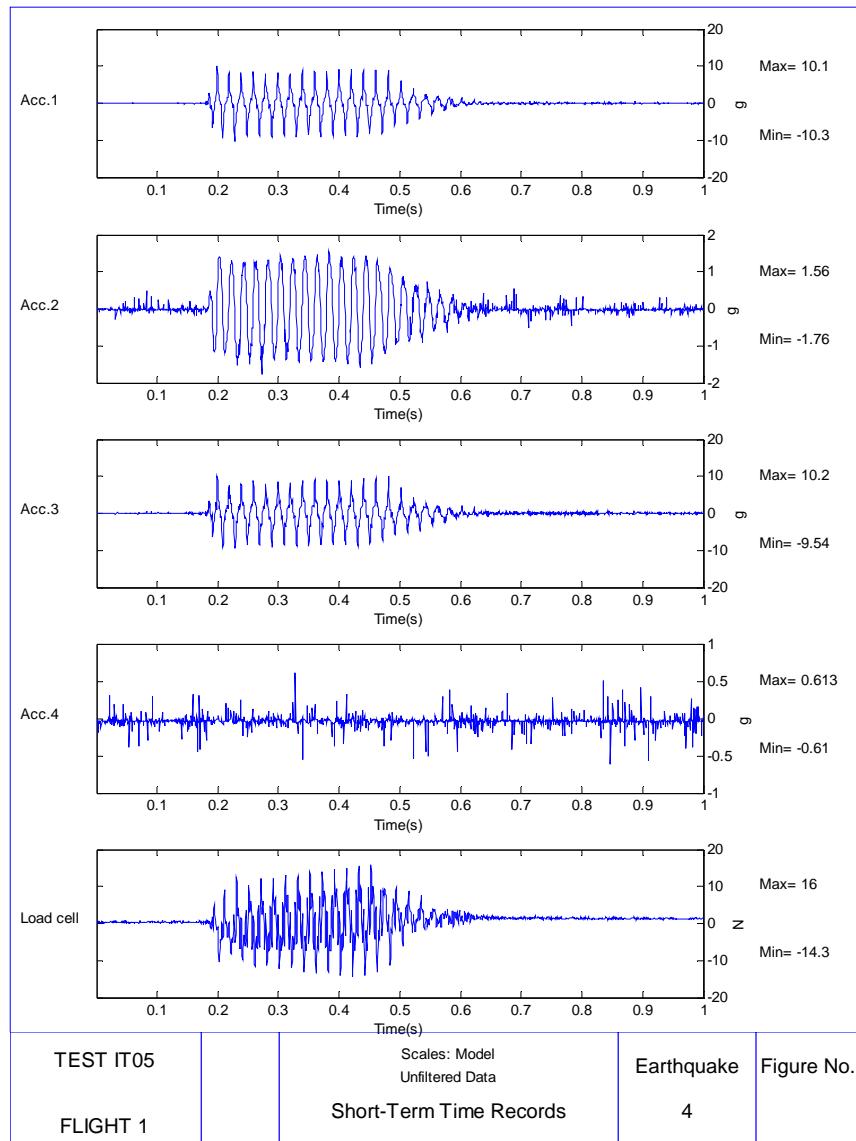
# CUED/D-SOILS/TR339



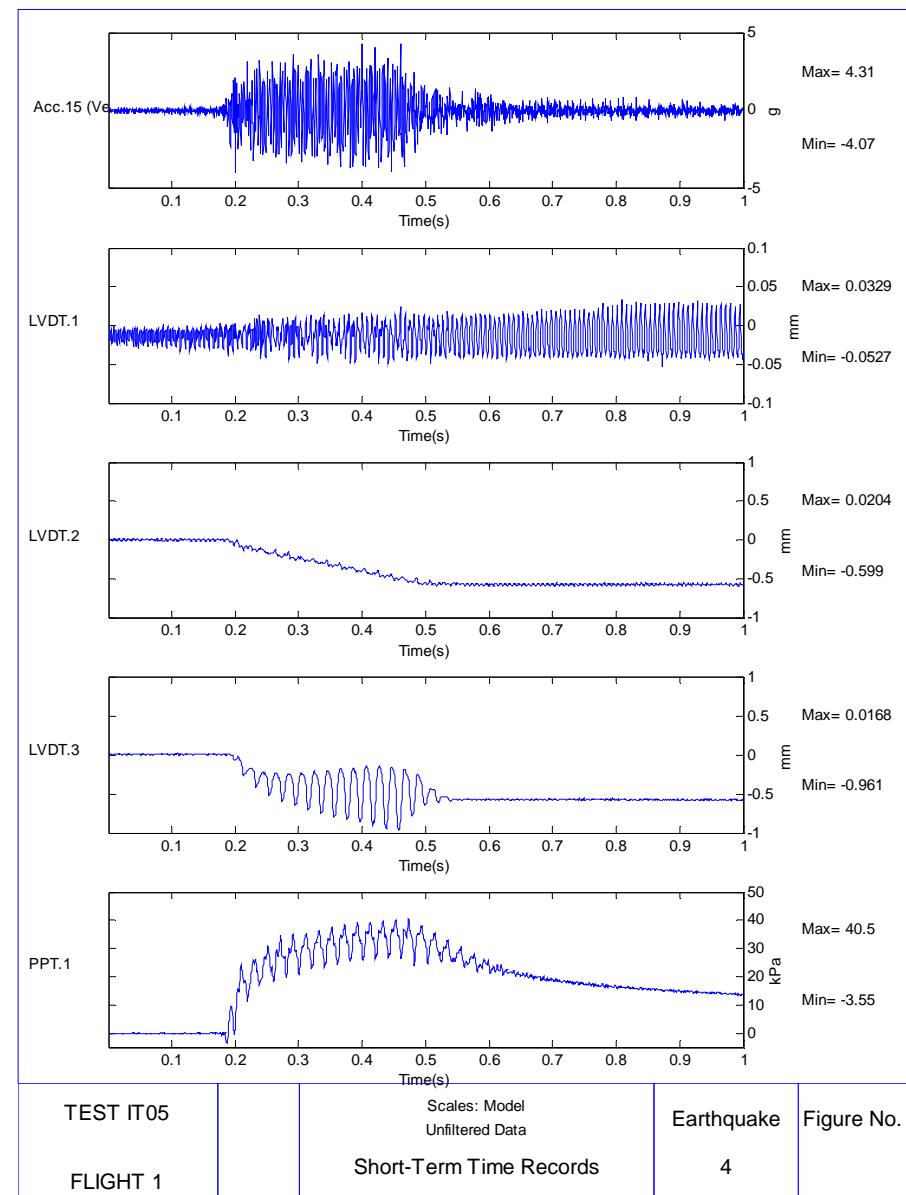
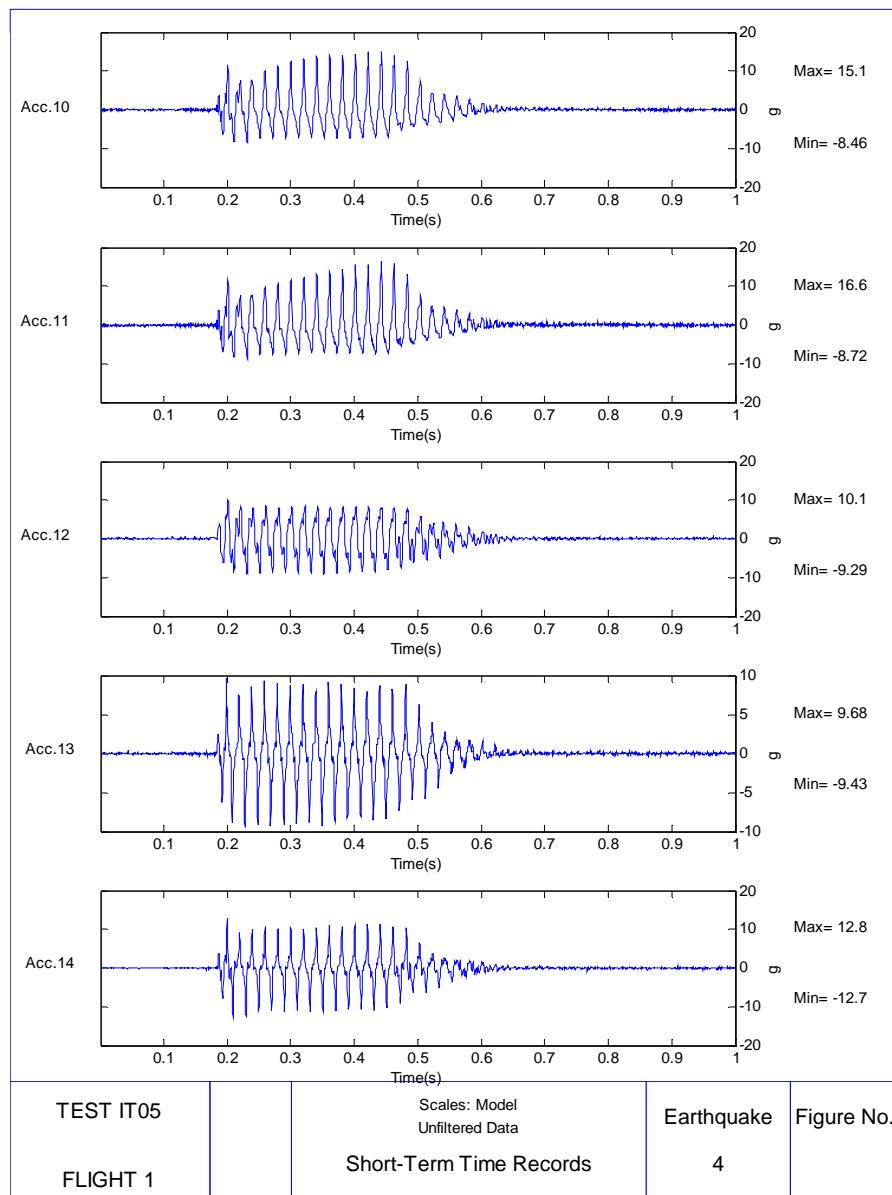
# CUED/D-SOILS/TR339



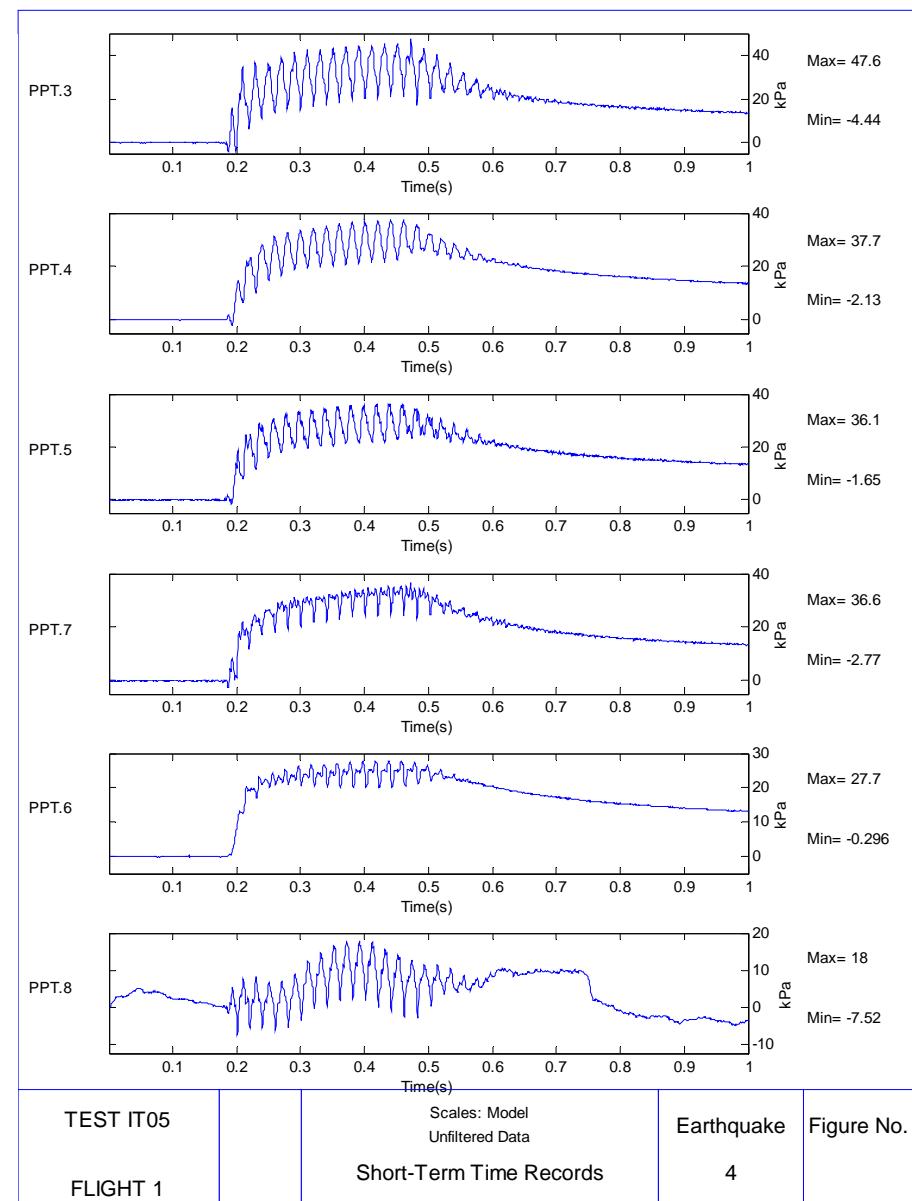
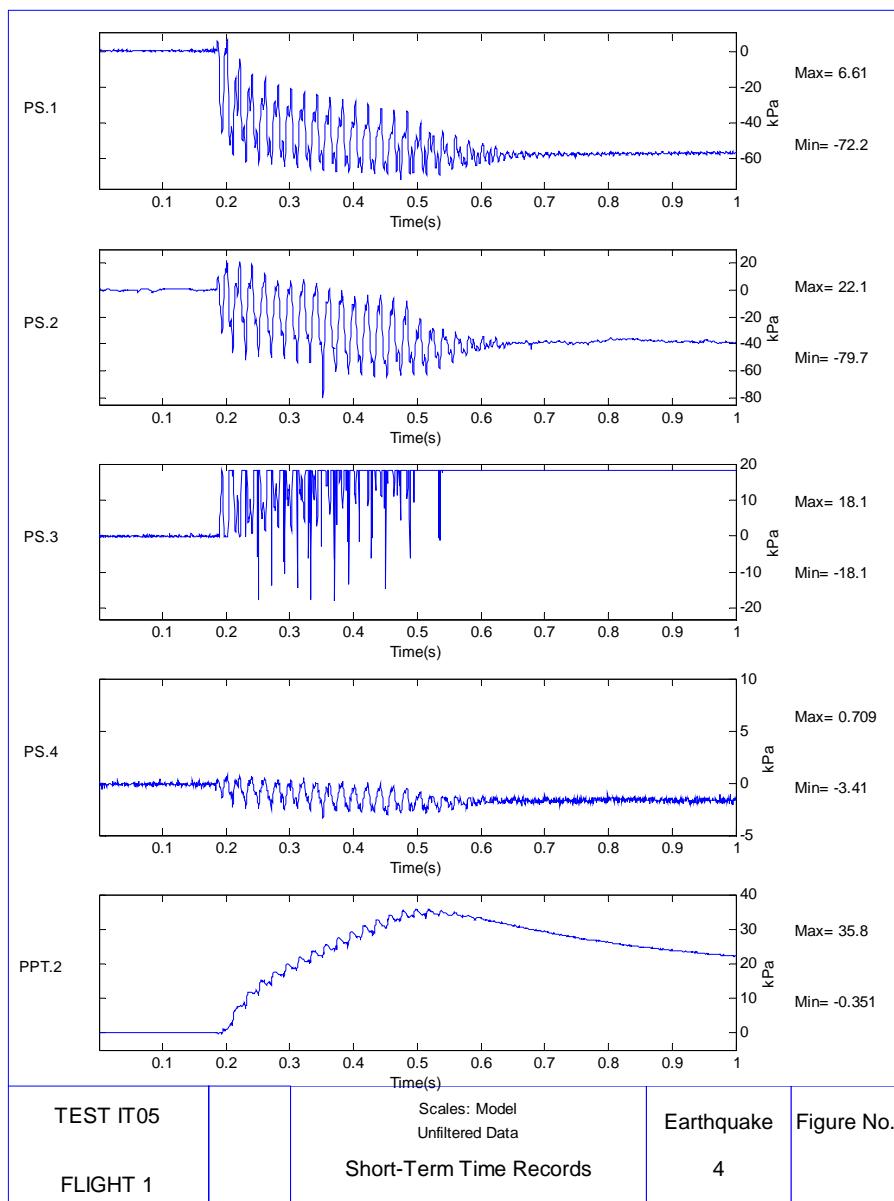
### 2.1.4 Data from IT05, Earthquake 4



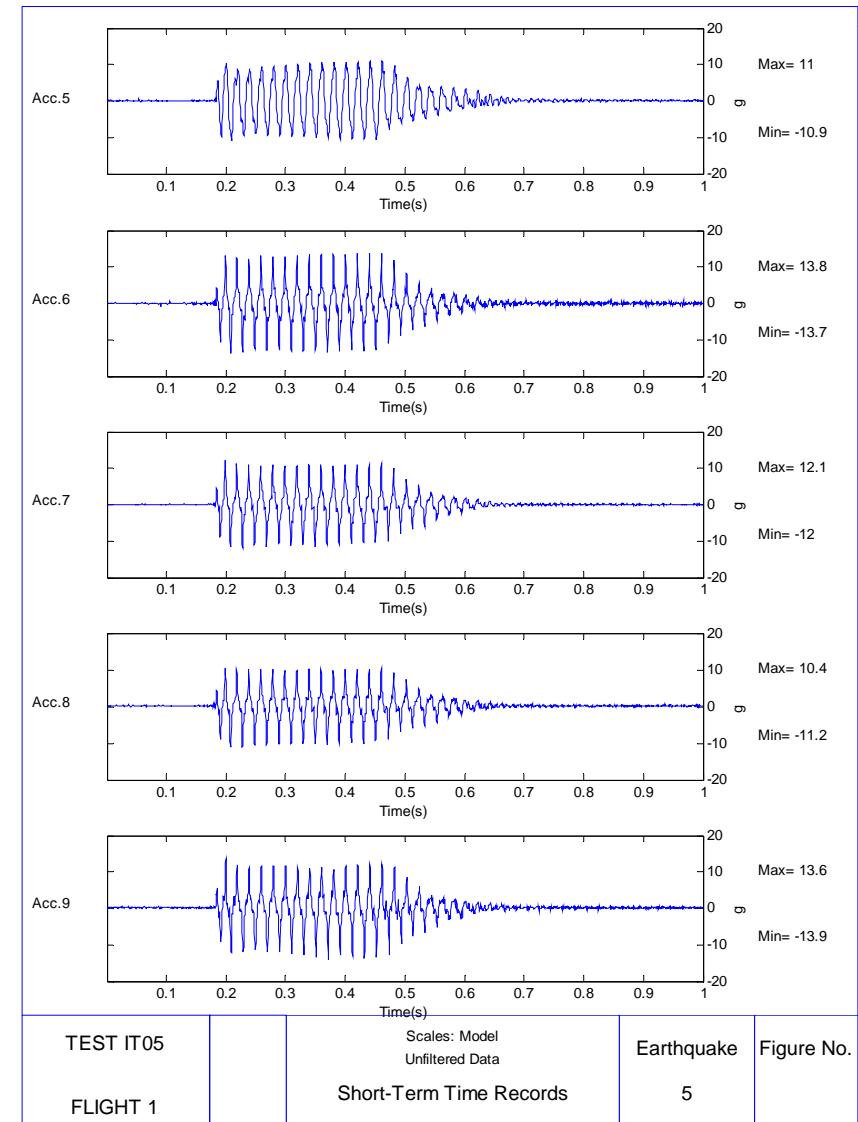
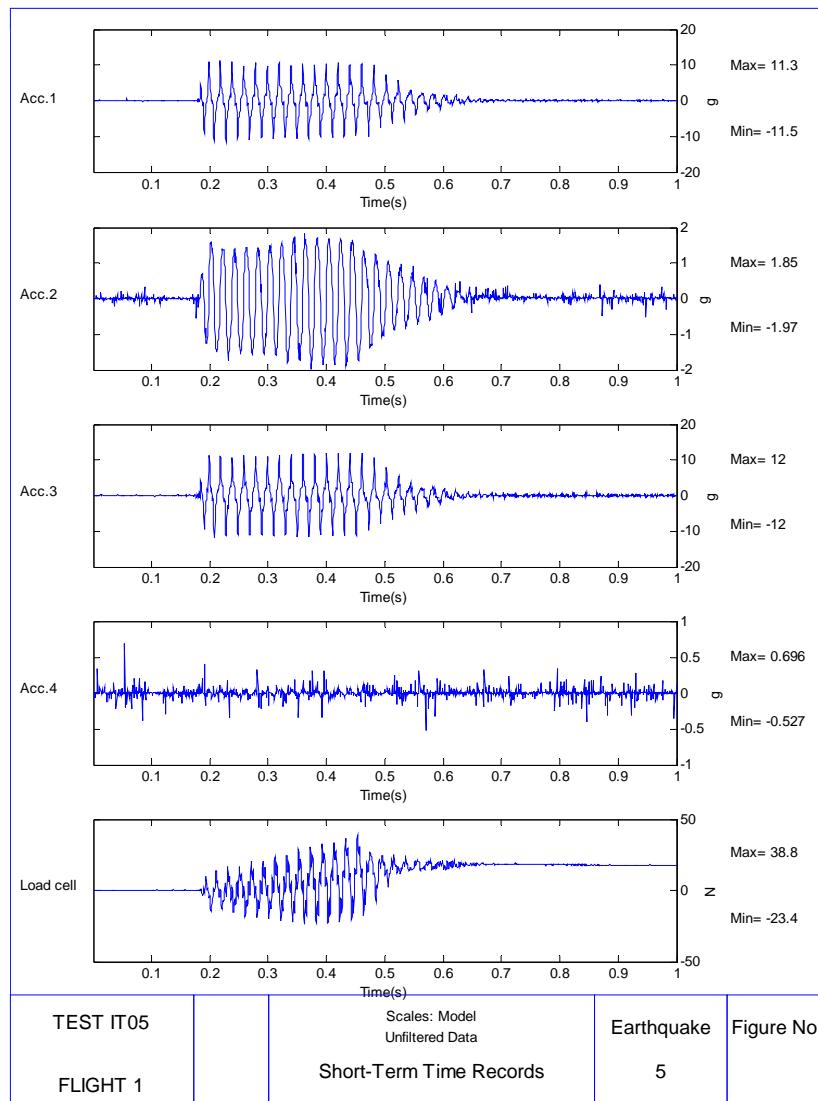
# CUED/D-SOILS/TR339



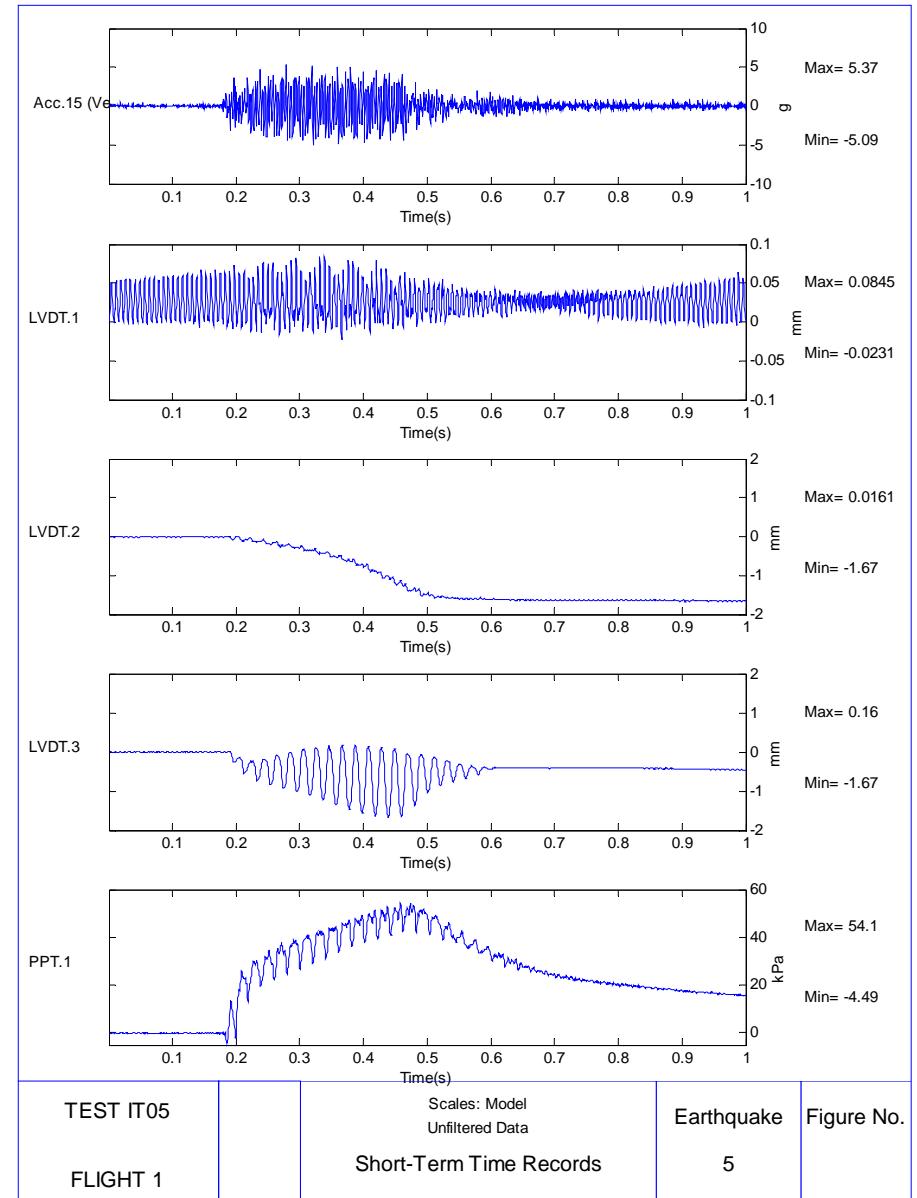
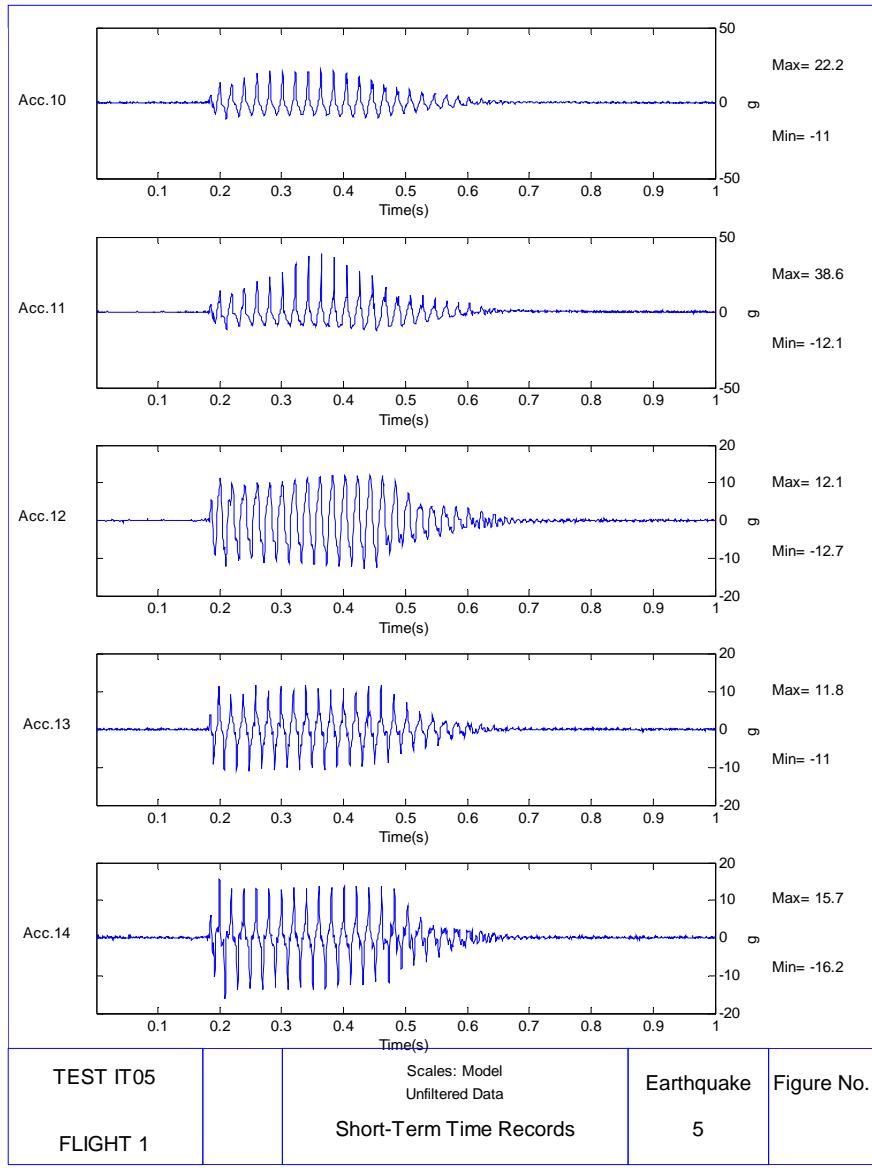
# CUED/D-SOILS/TR339



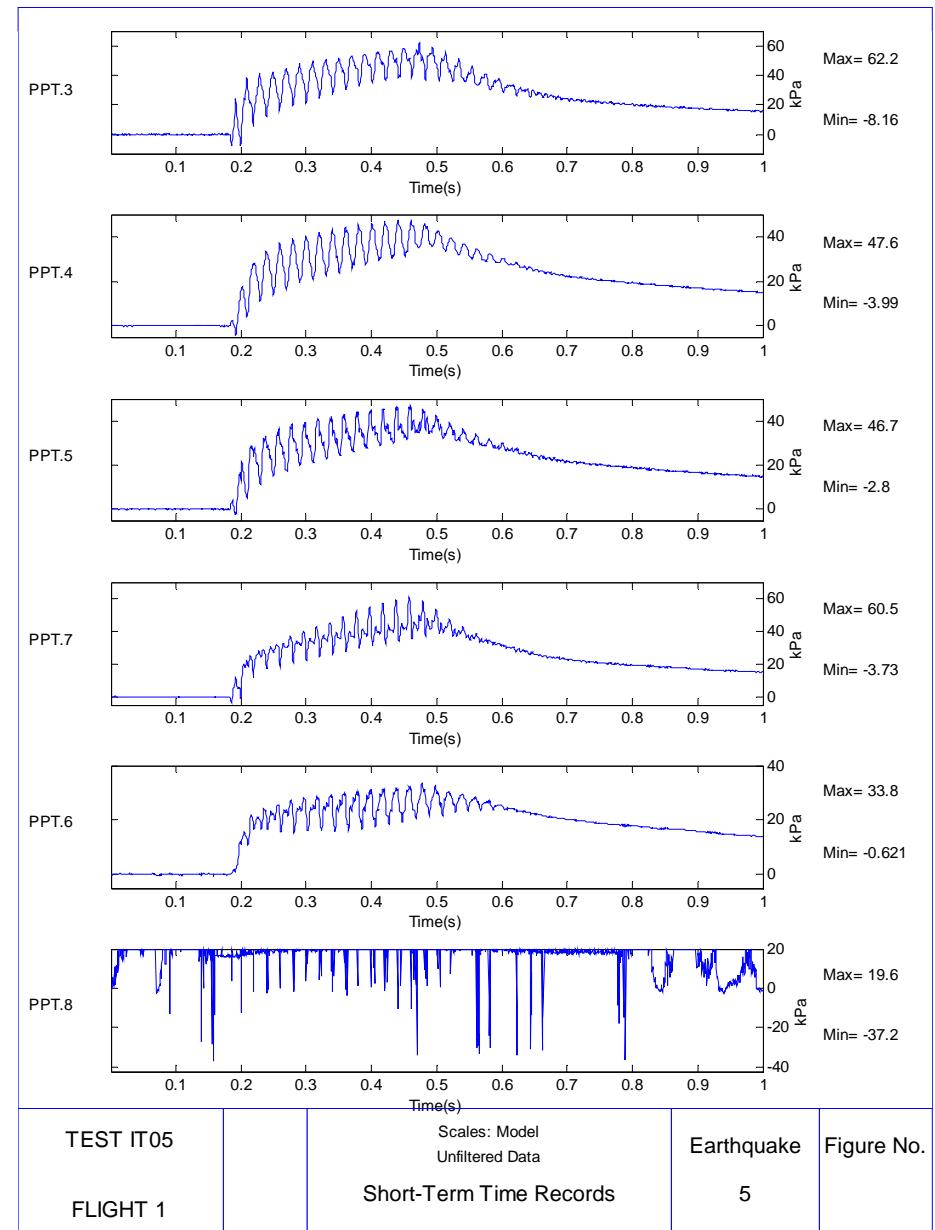
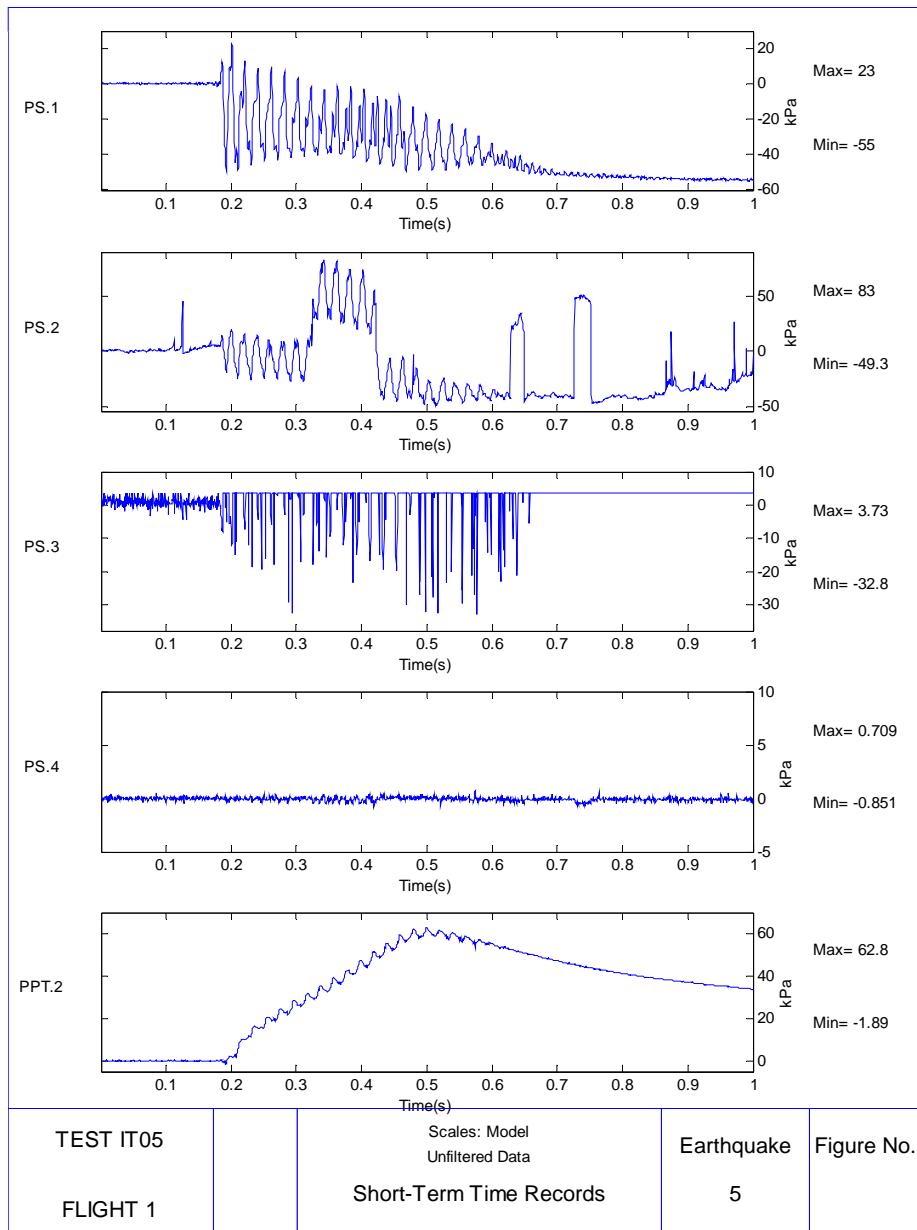
### 2.1.5 Data from IT05, Earthquake 5



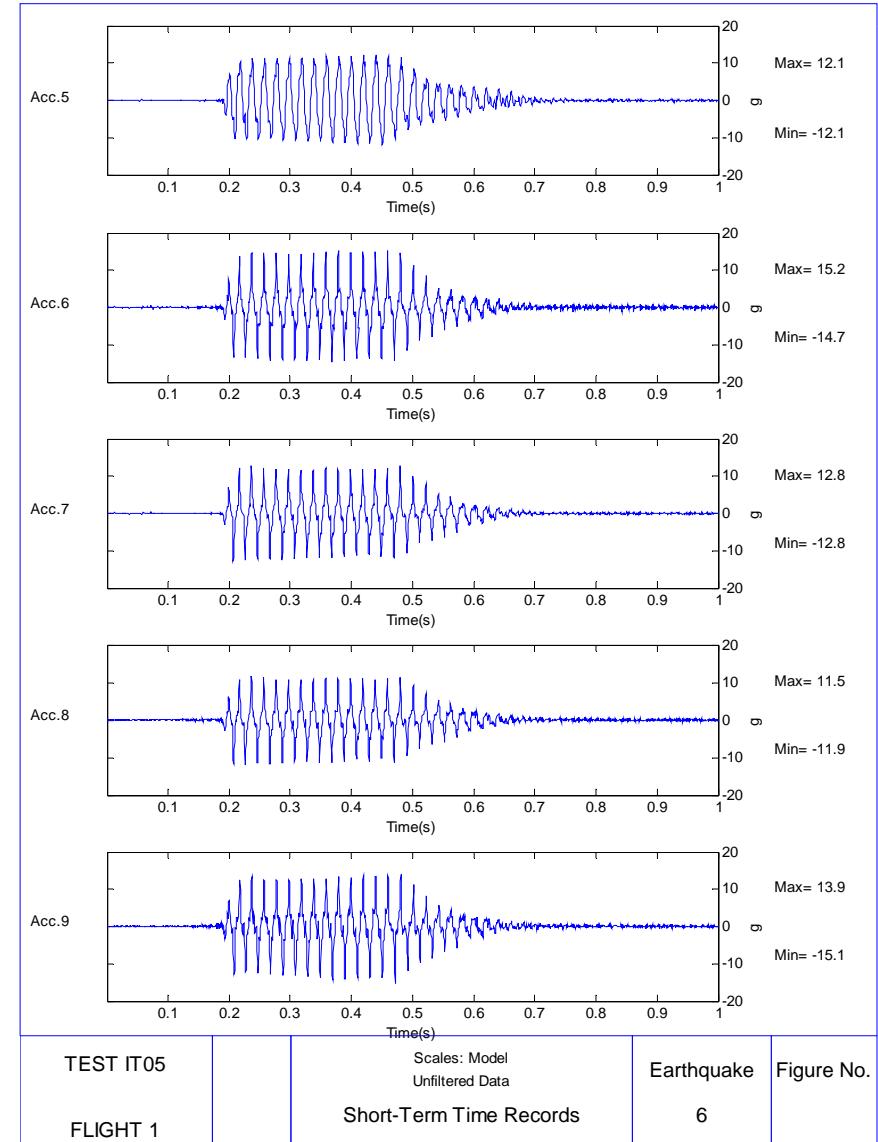
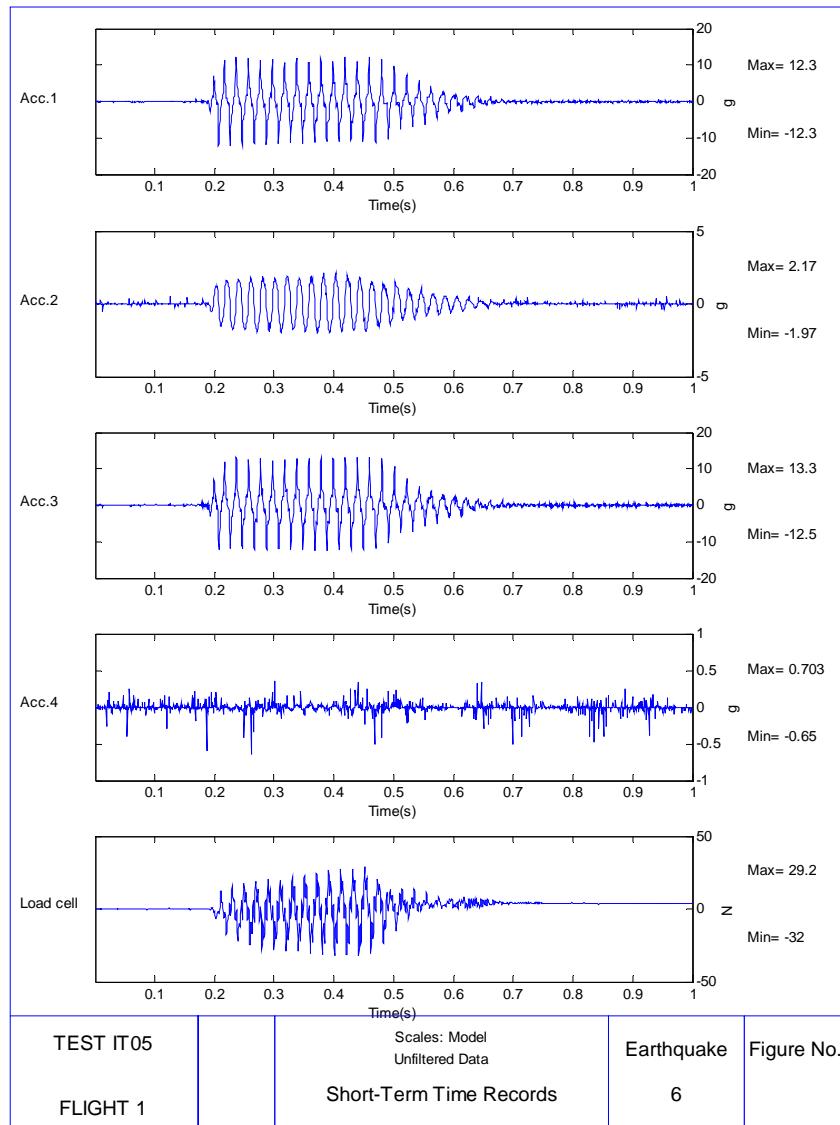
# CUED/D-SOILS/TR339



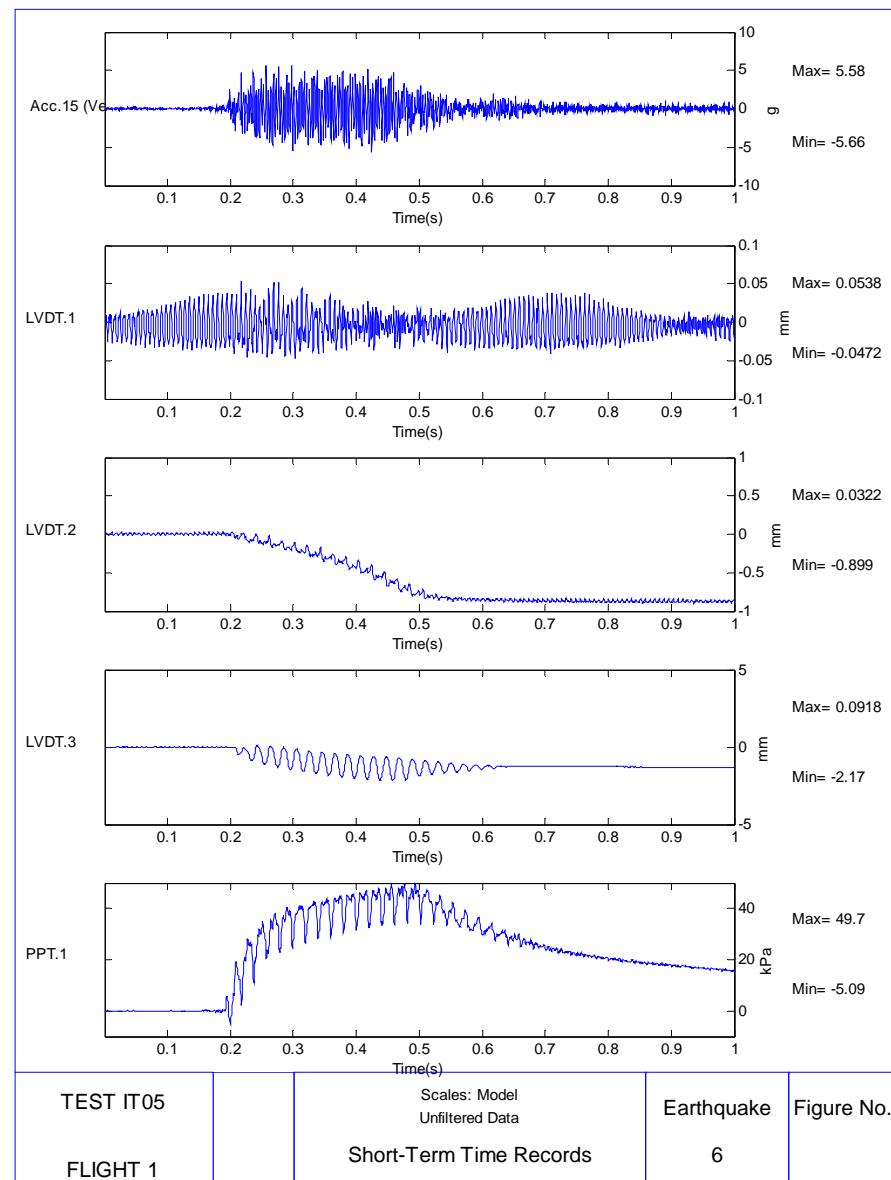
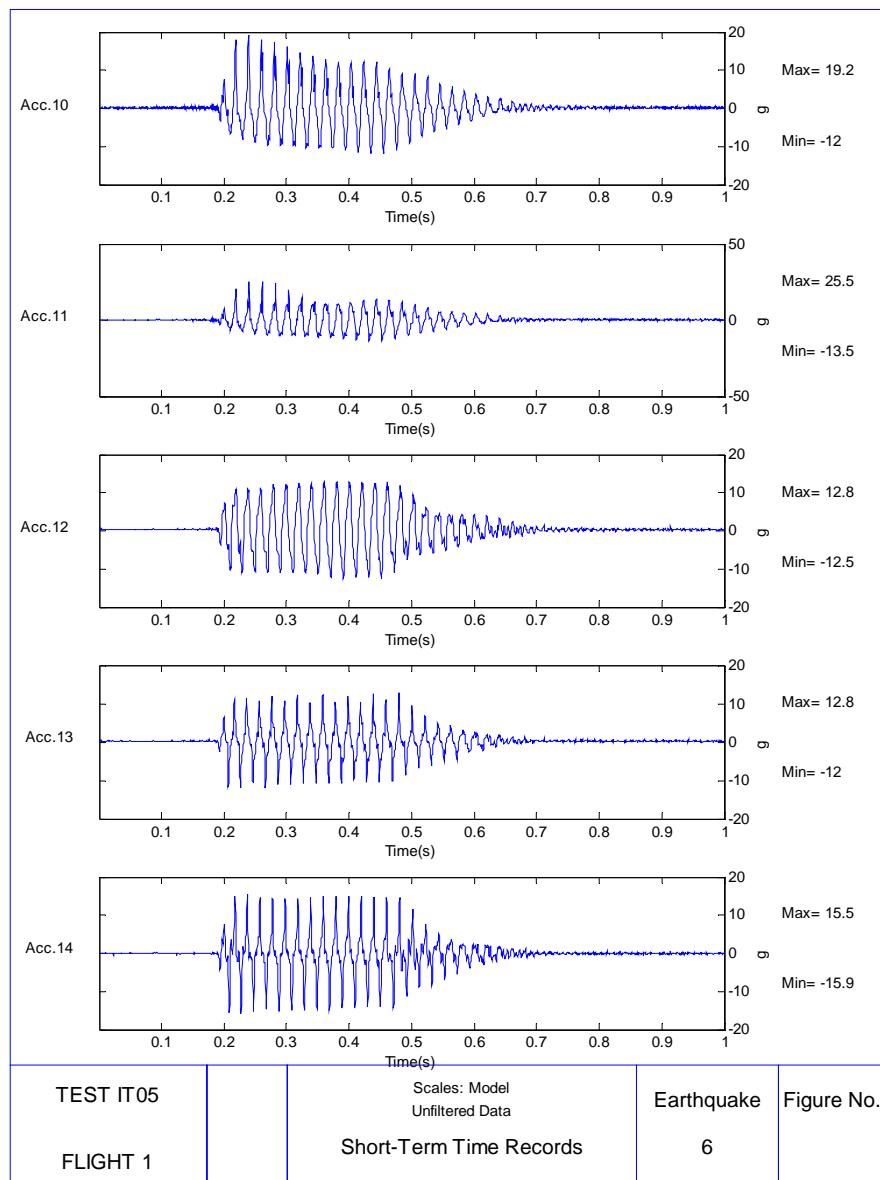
# CUED/D-SOILS/TR339



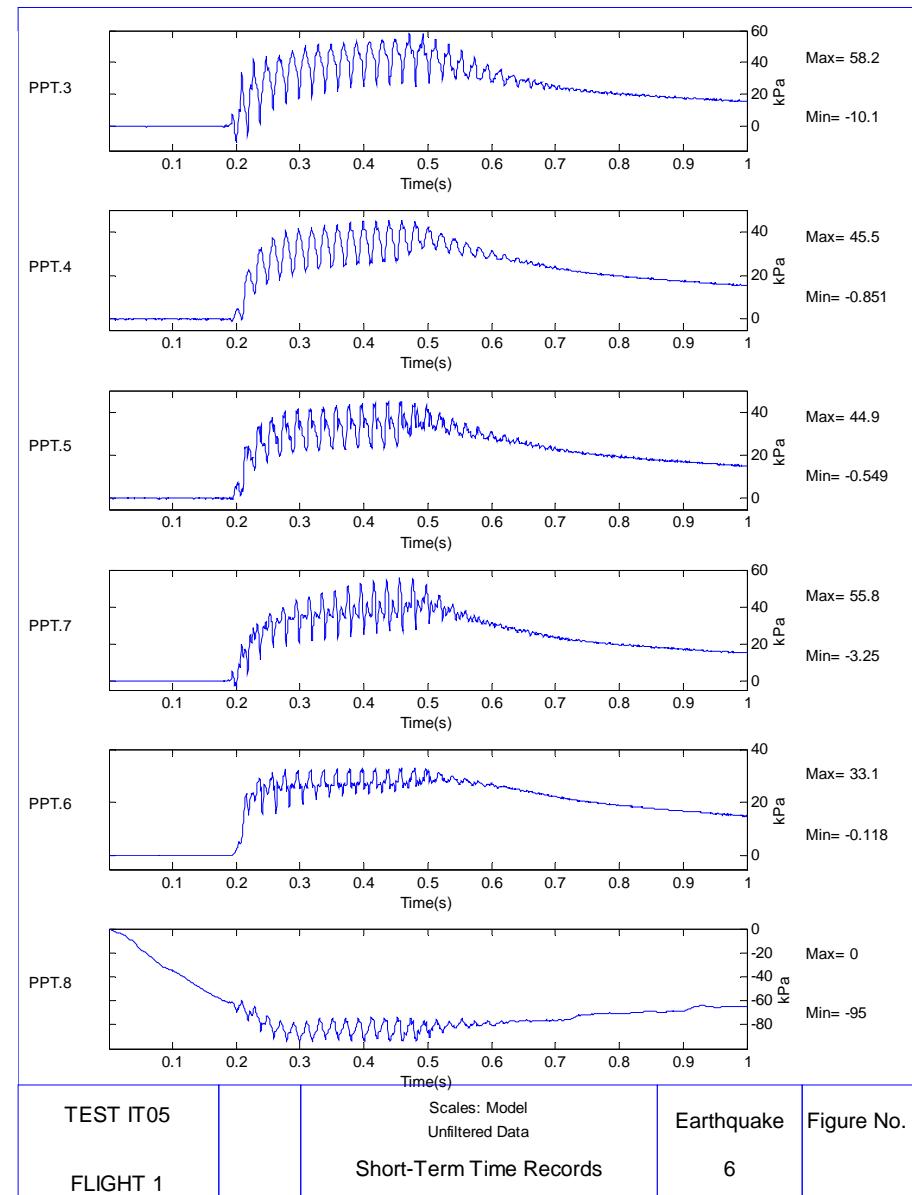
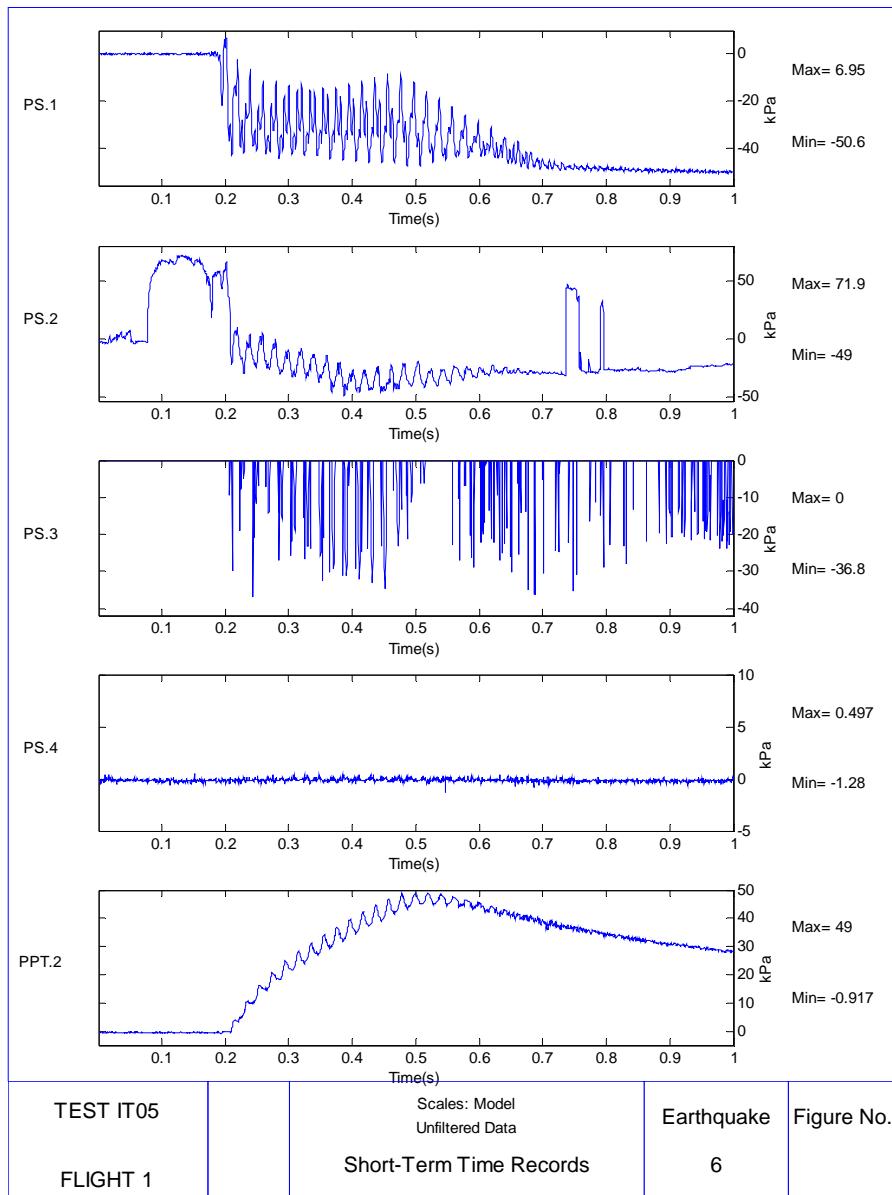
### 2.1.6 Data from IT05, Earthquake 6



# CUED/D-SOILS/TR339

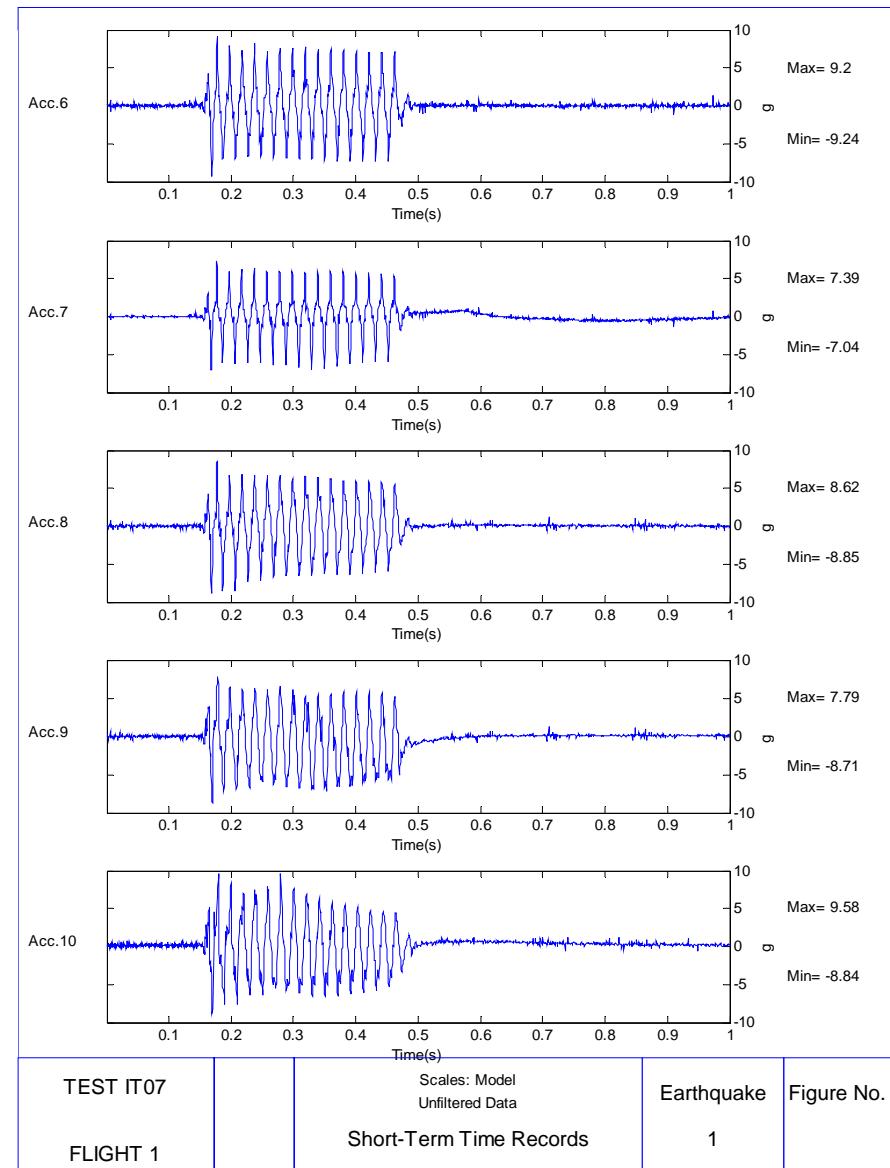
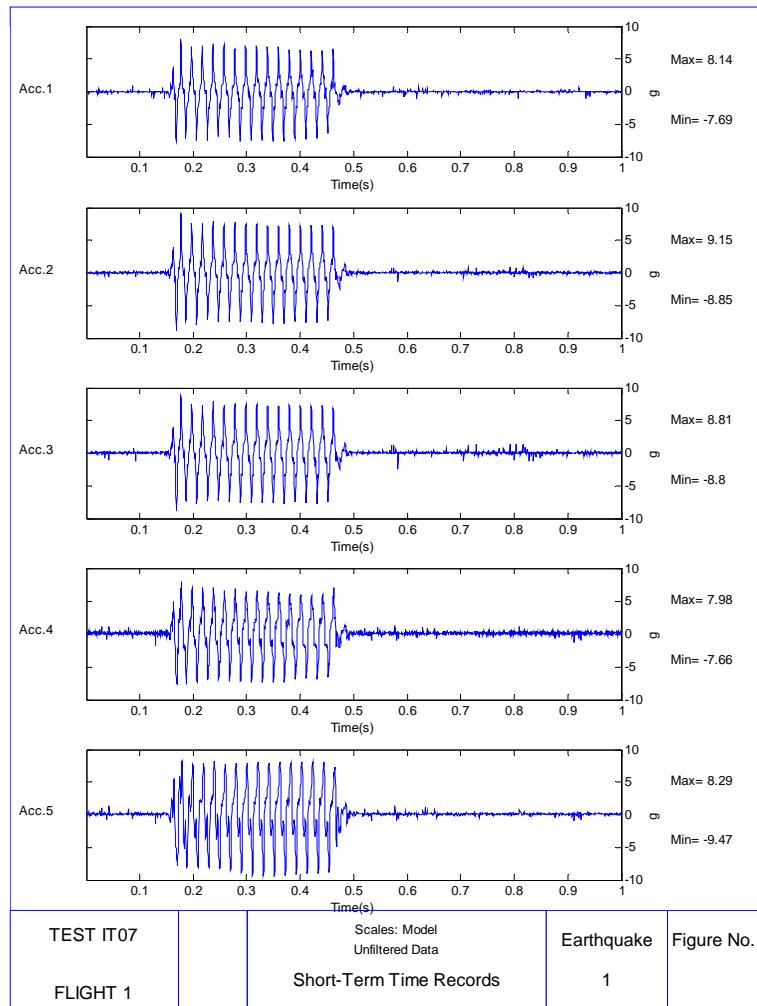


# CUED/D-SOILS/TR339

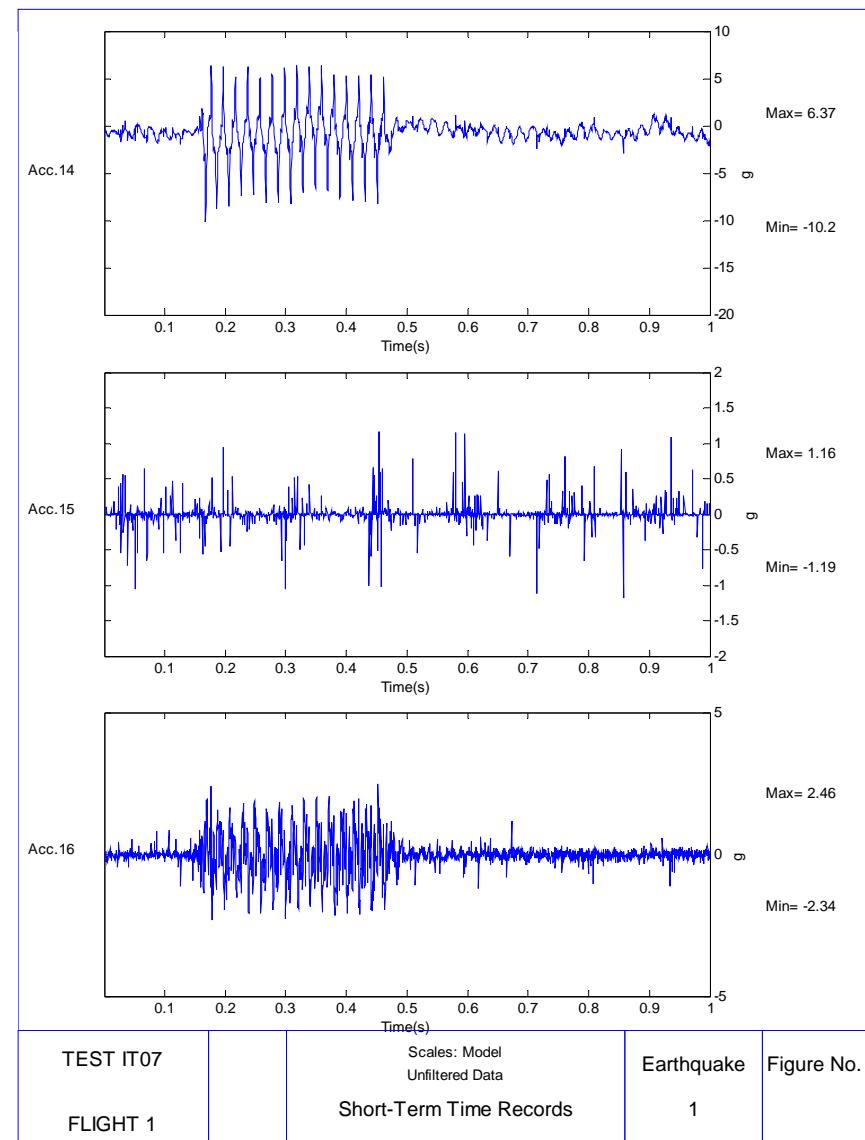
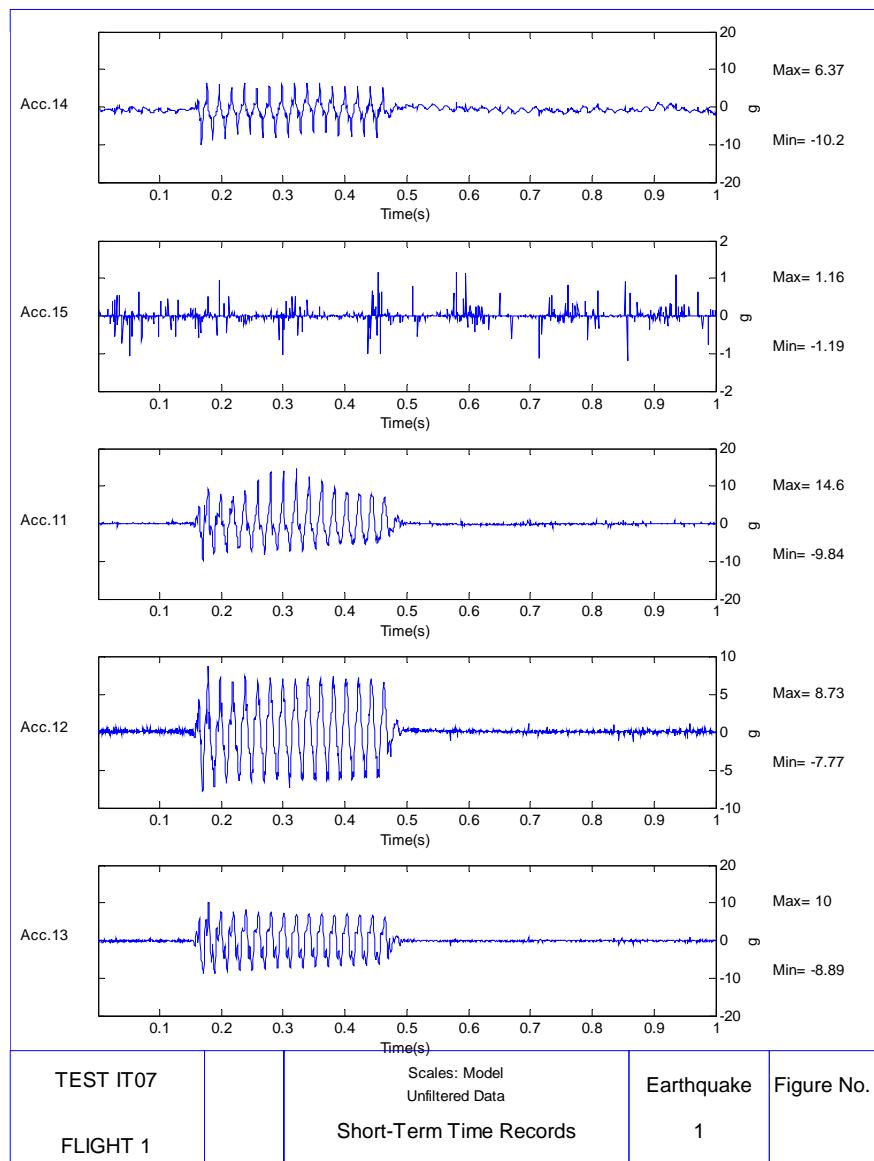


## 2.2 Results from test IT07

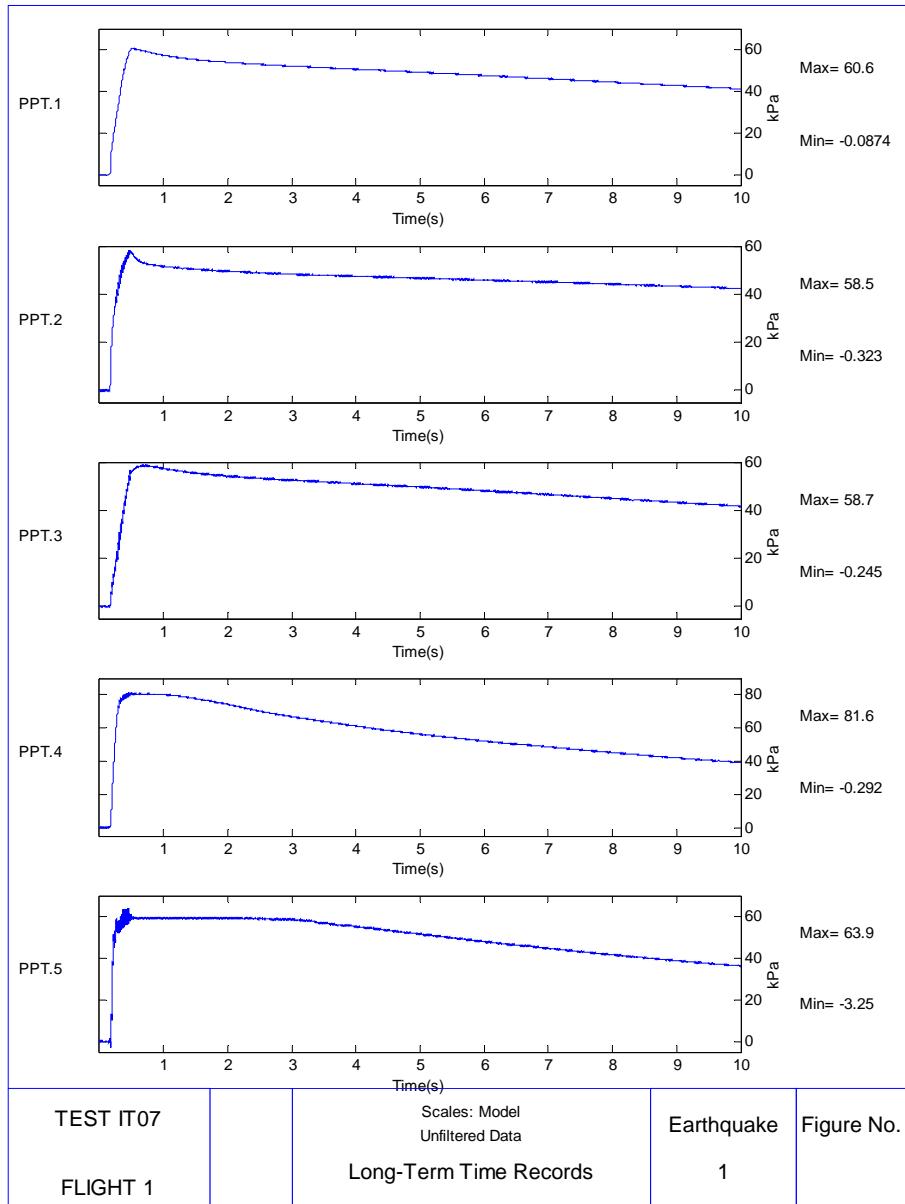
### 2.2.1 IT07, Earthquake 1



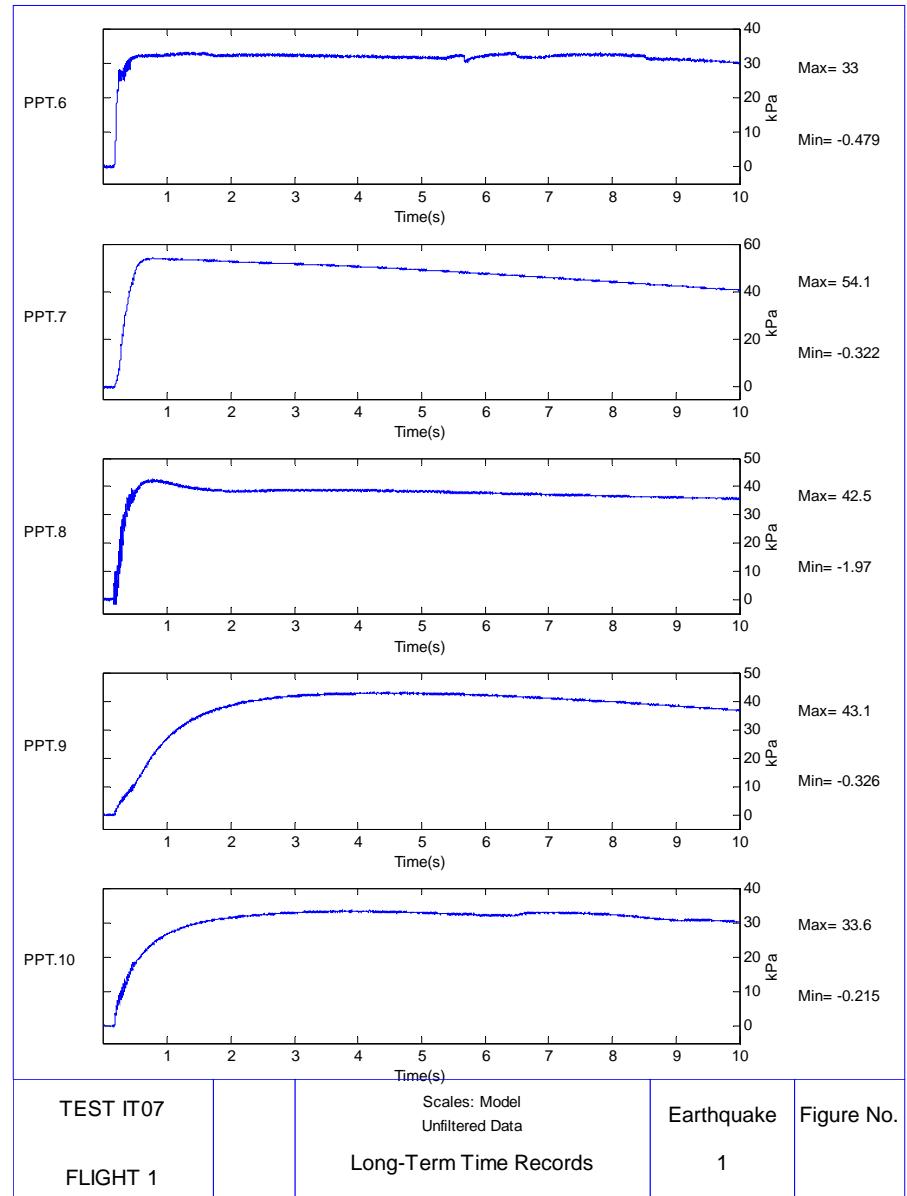
# CUED/D-SOILS/TR339



# CUED/D-SOILS/TR339

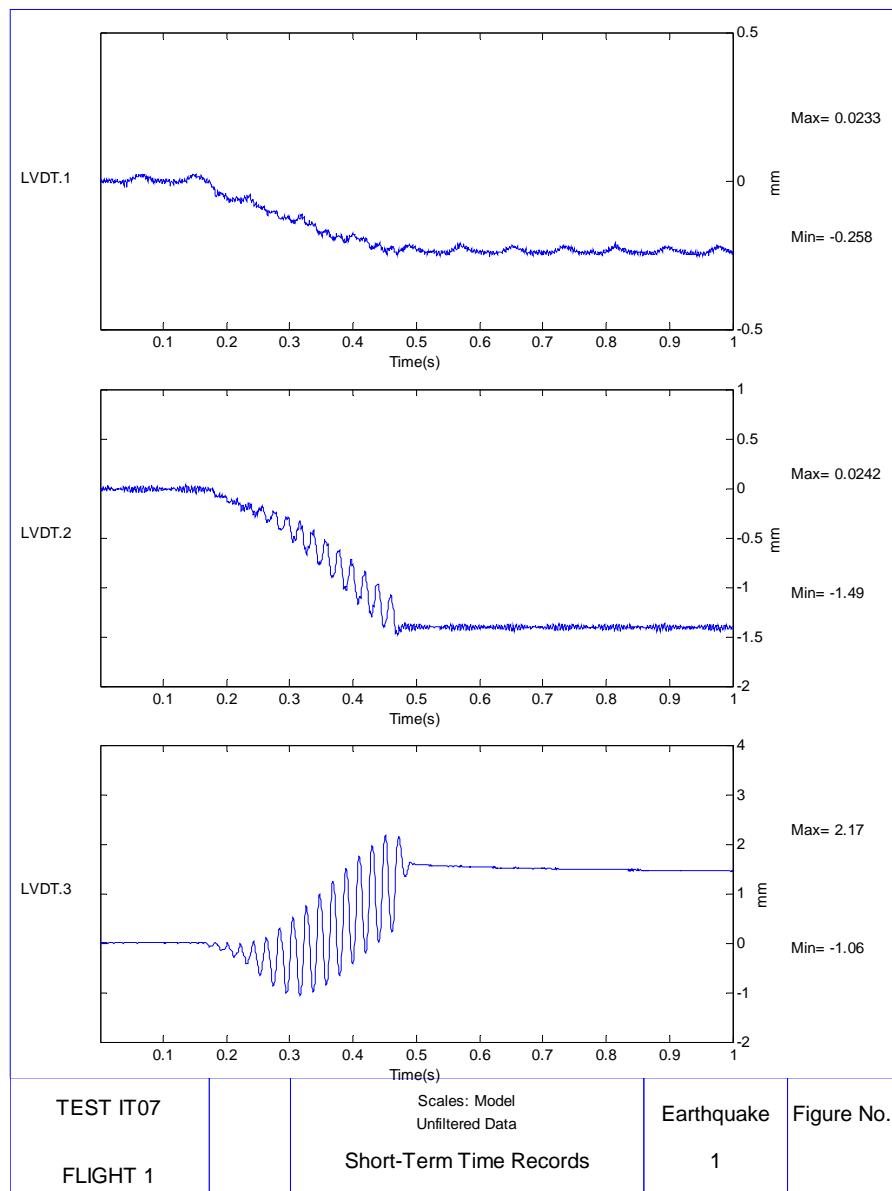


TEST IT07		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Long-Term Time Records	1	

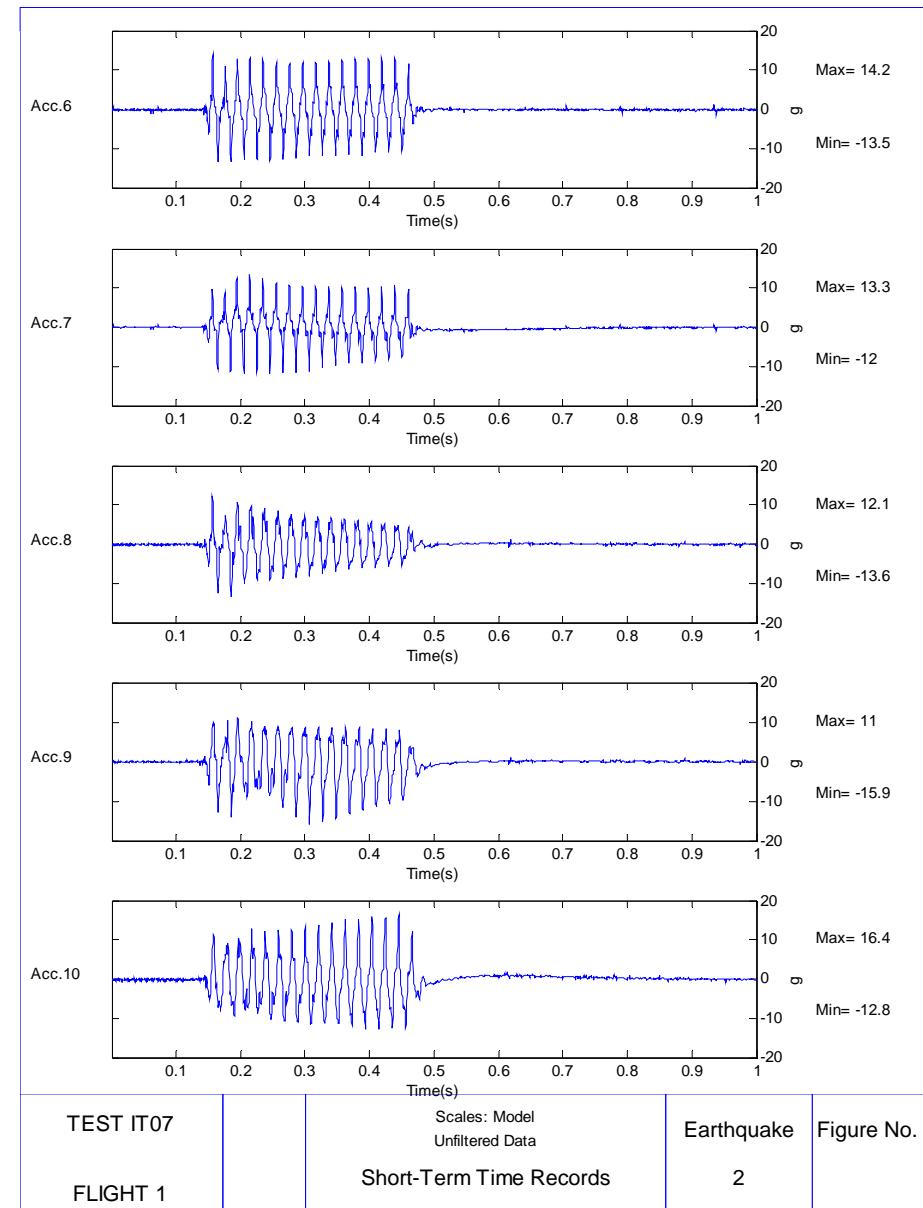
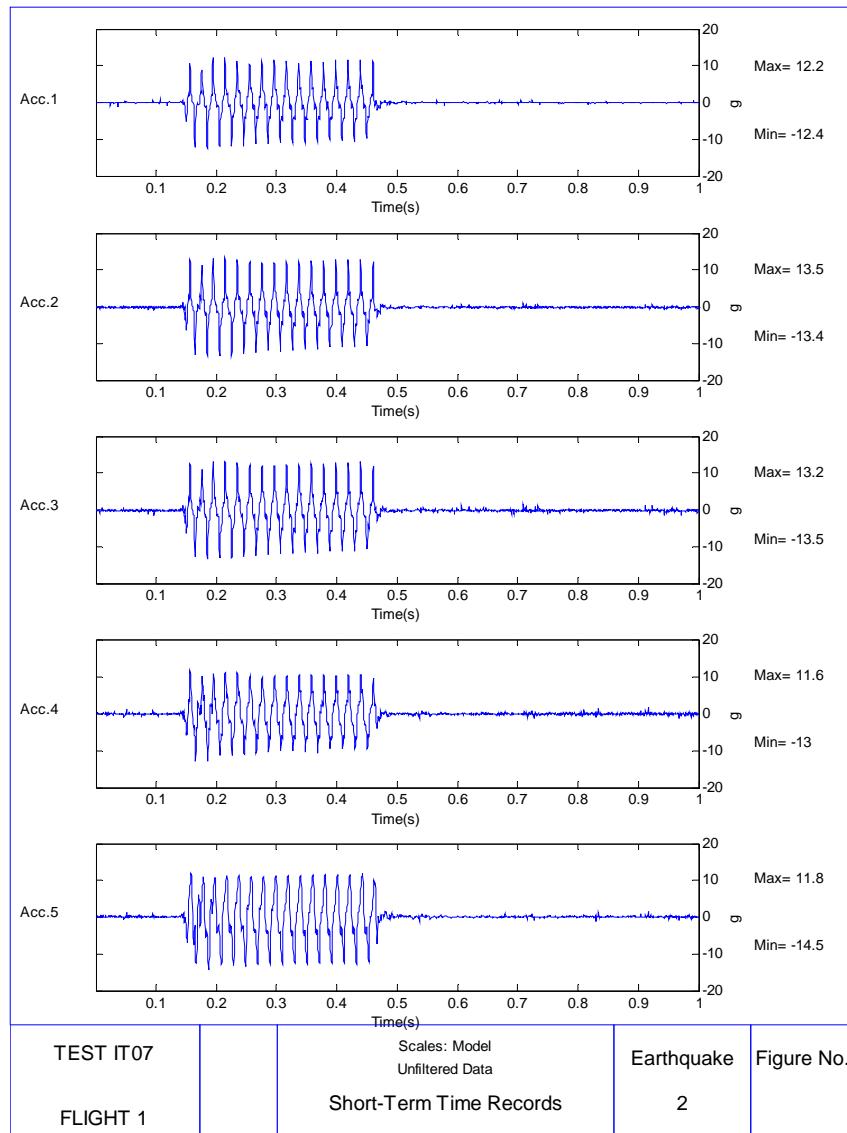


TEST IT07		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Long-Term Time Records	1	

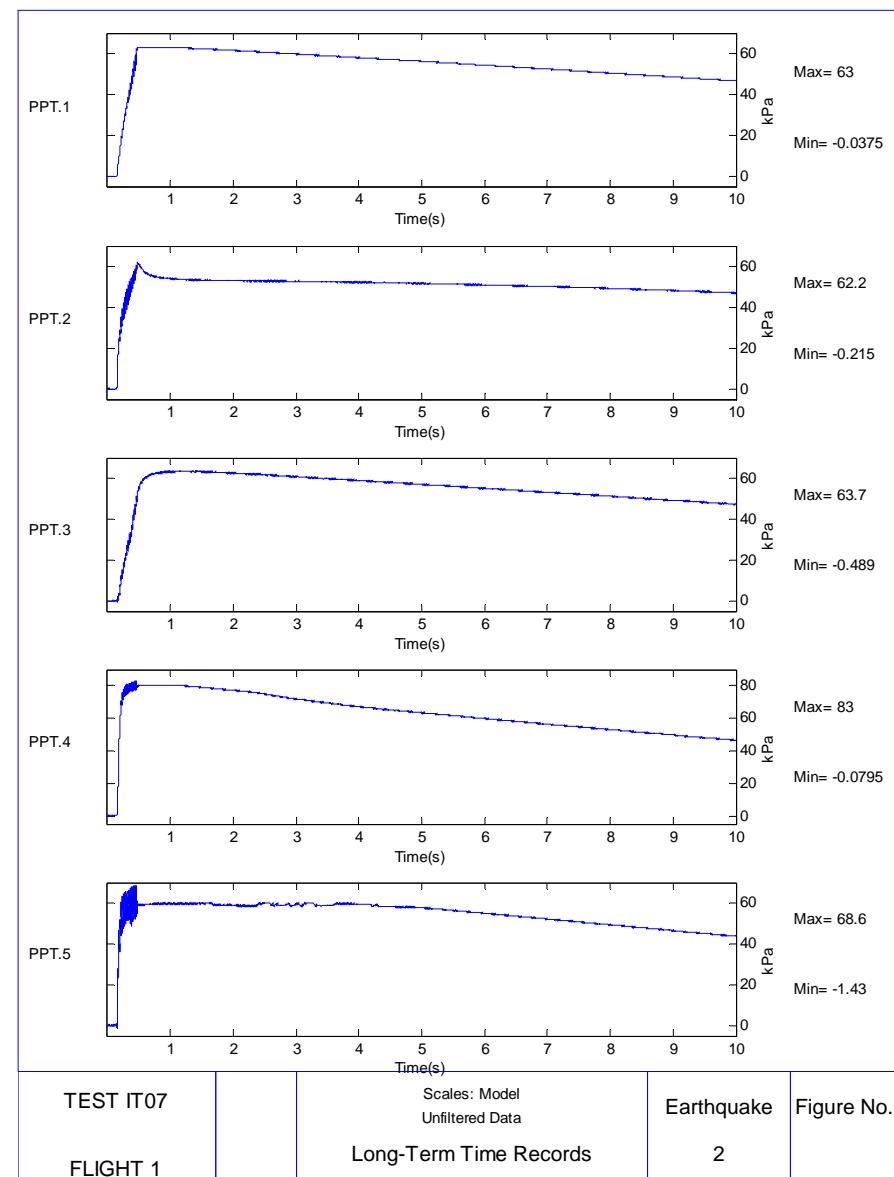
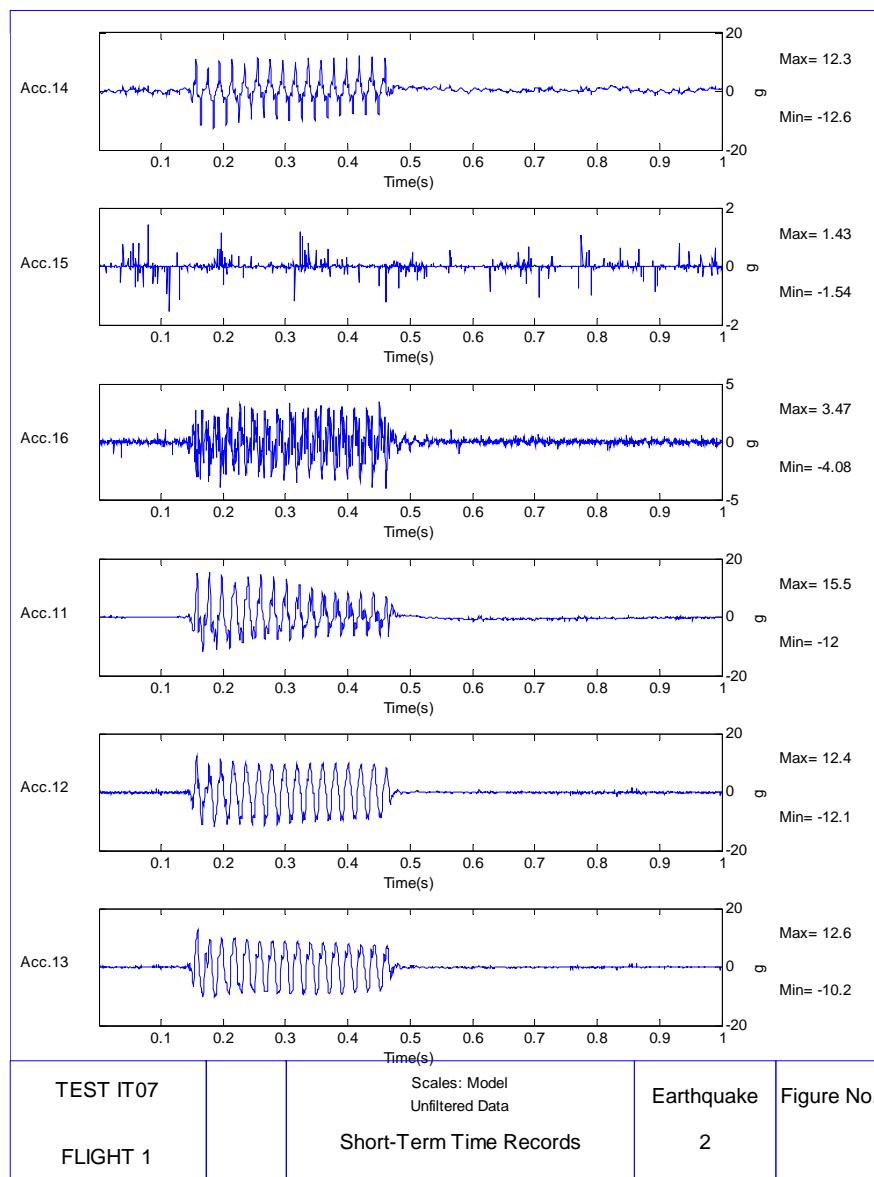
CUED/D-SOILS/TR339



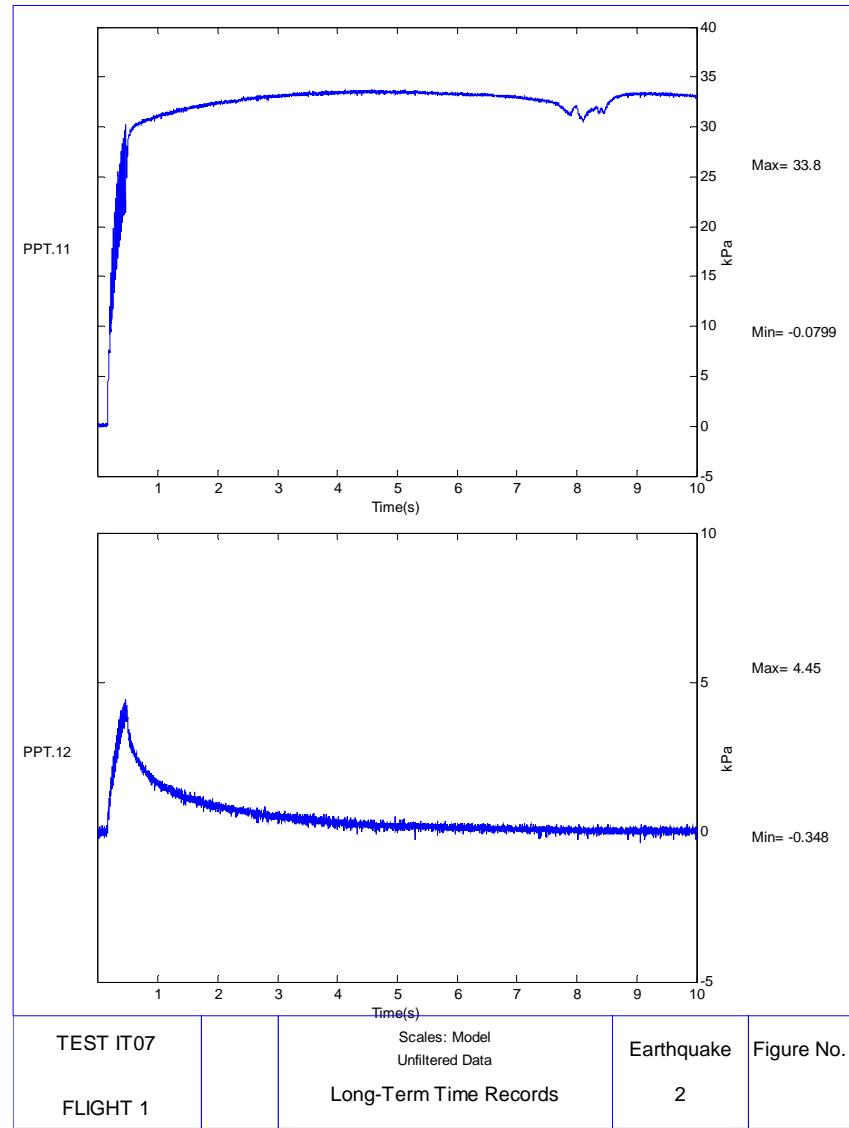
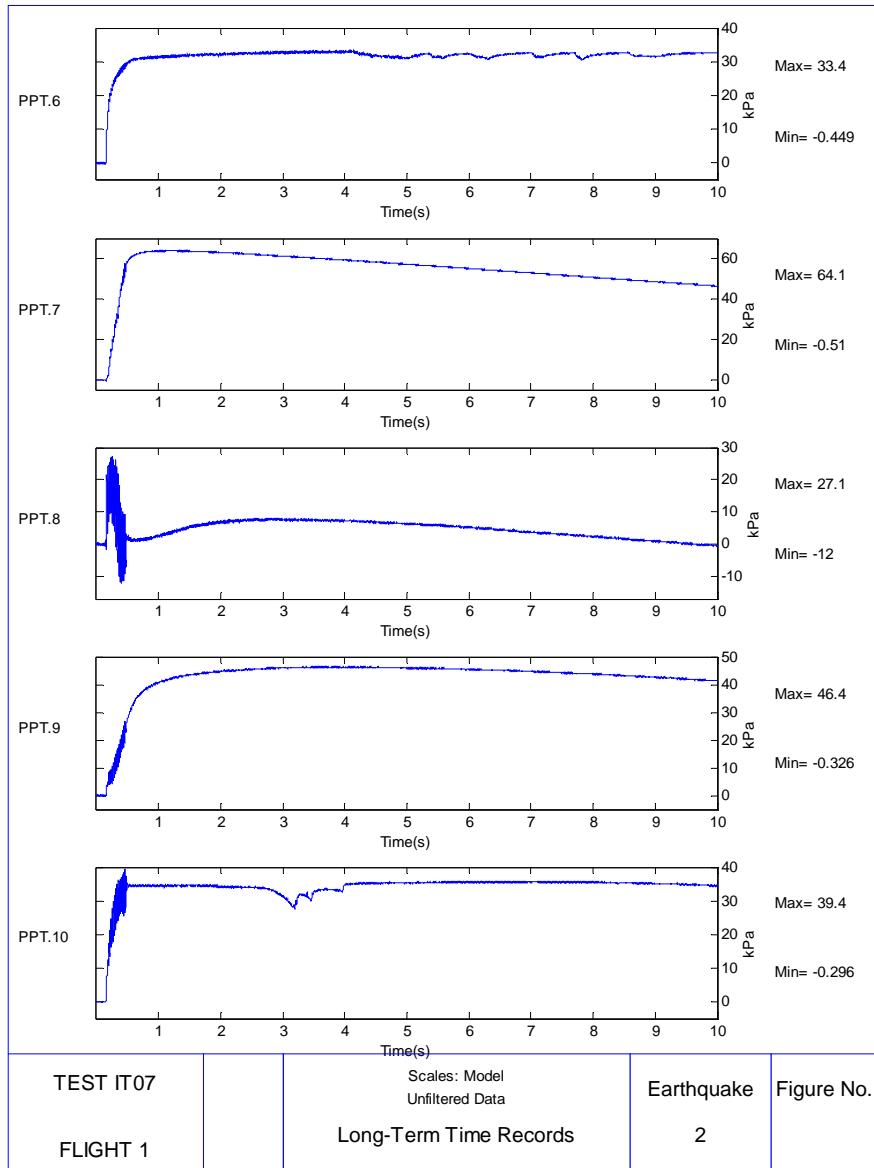
## 2.2.2 IT07, Earthquake 2



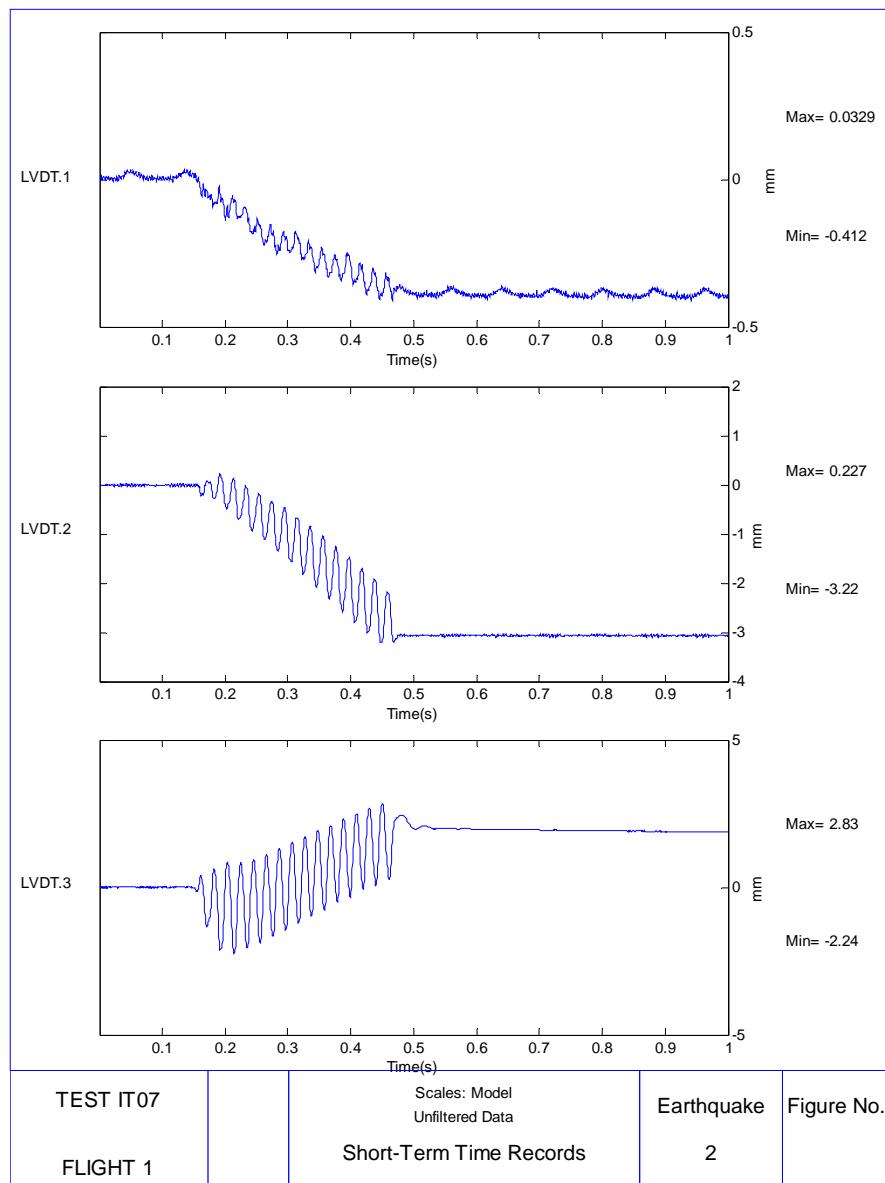
# CUED/D-SOILS/TR339



# CUED/D-SOILS/TR339

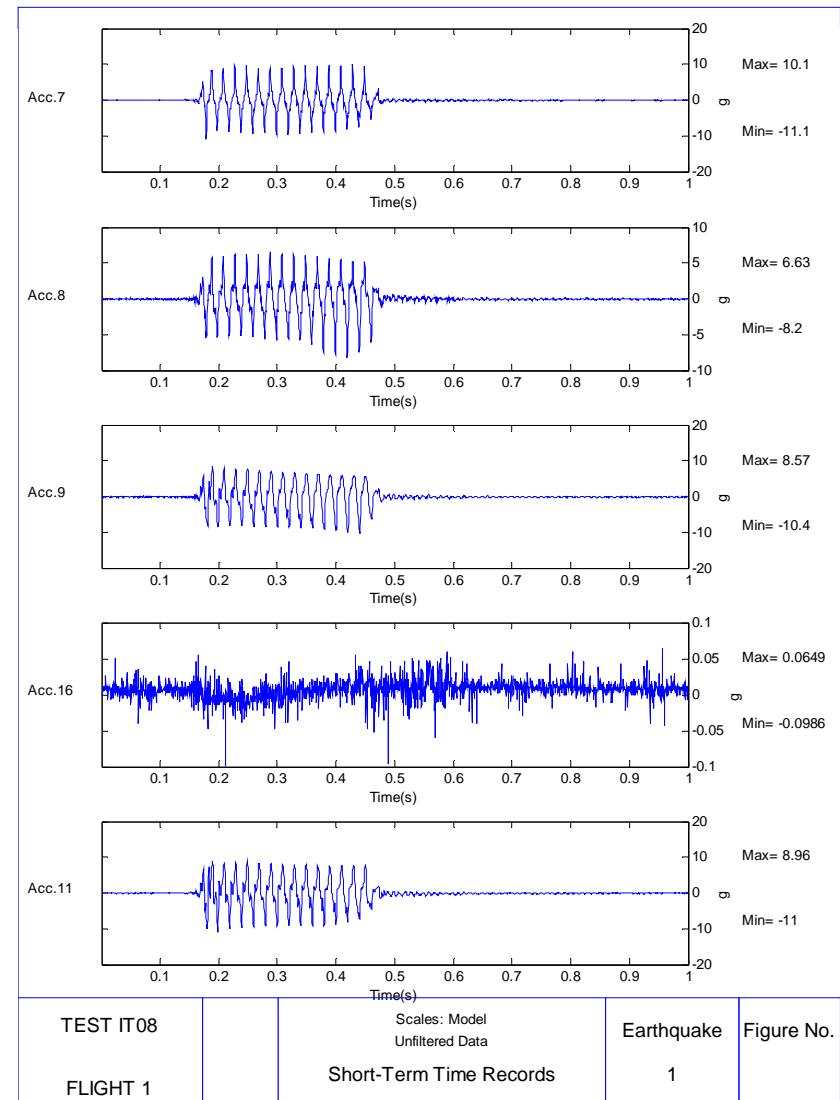
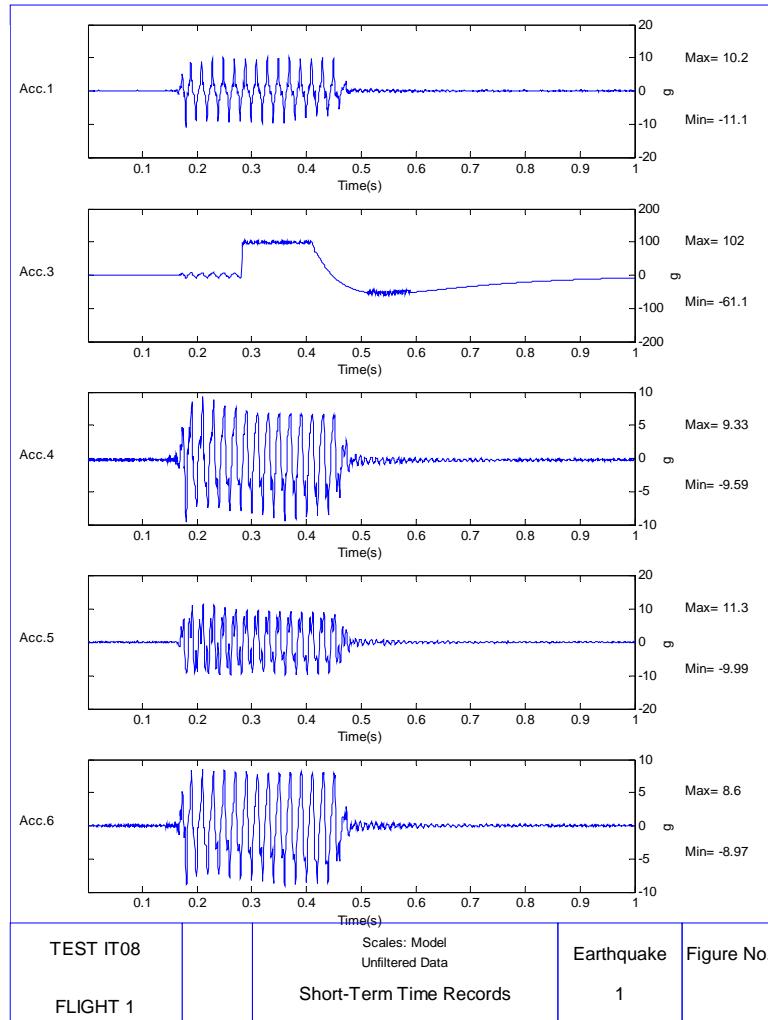


CUED/D-SOILS/TR339

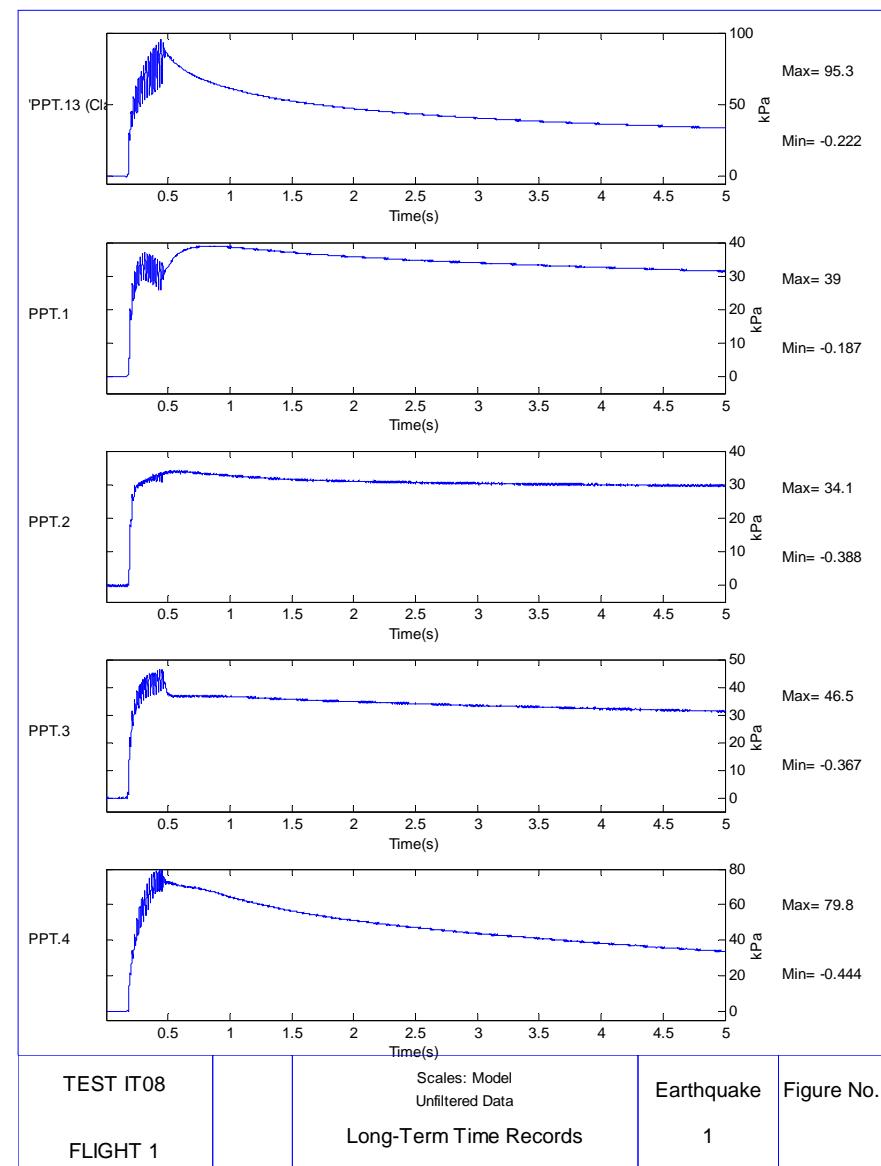
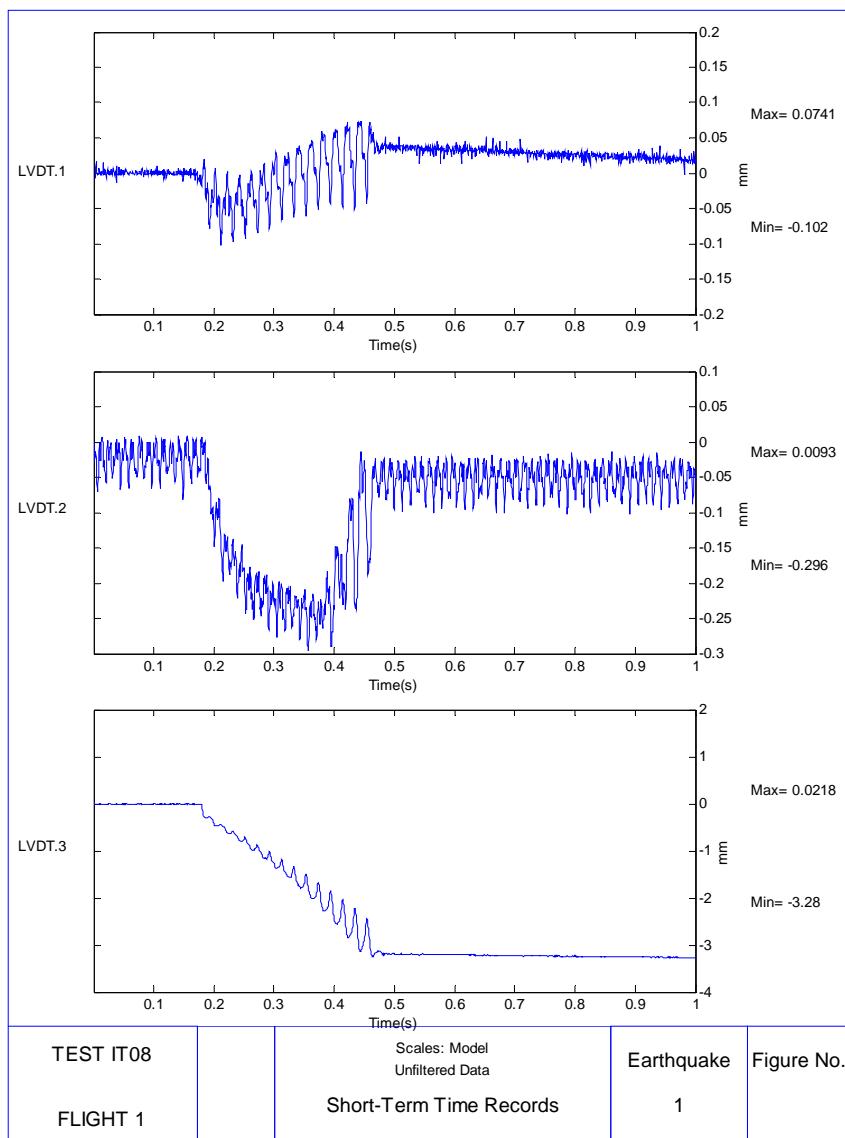


## 2.3 Results from test IT08

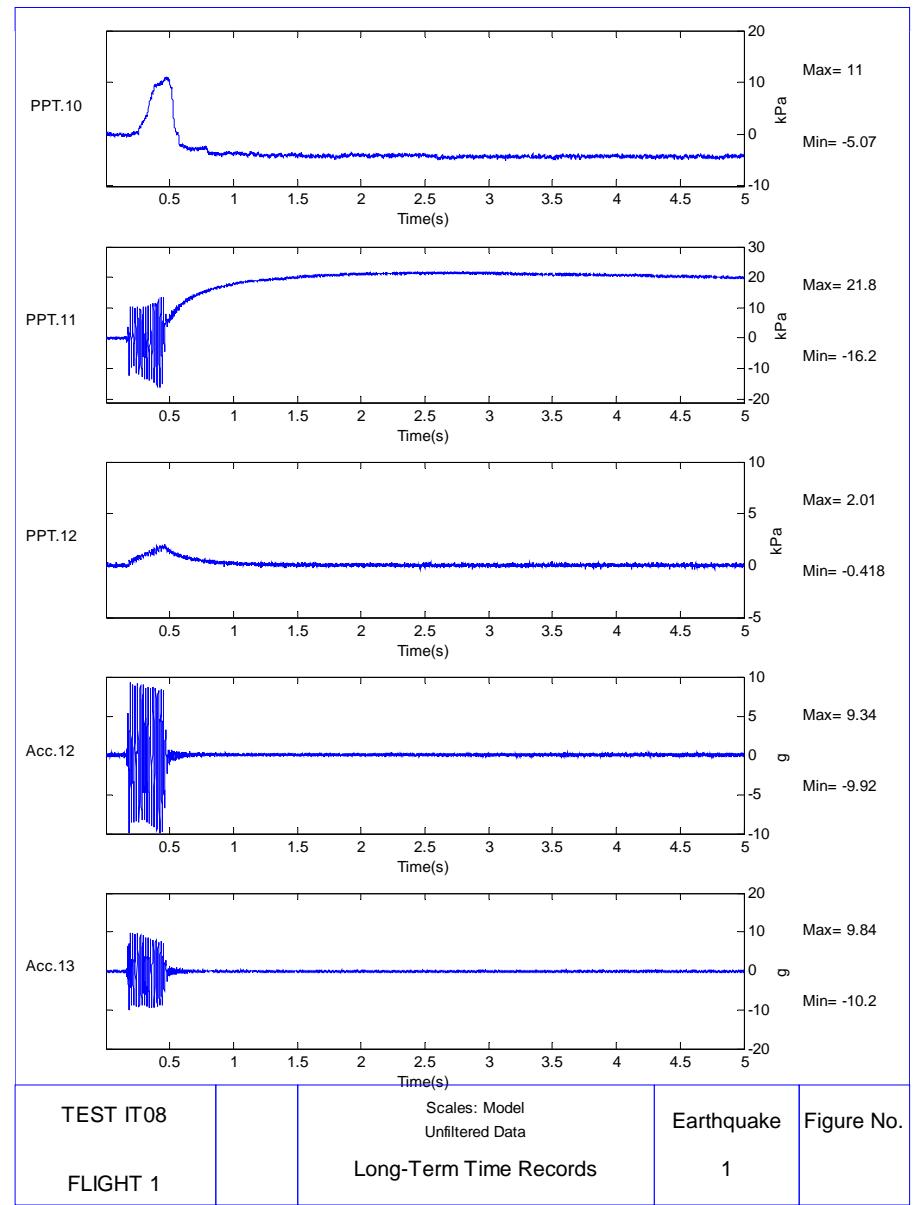
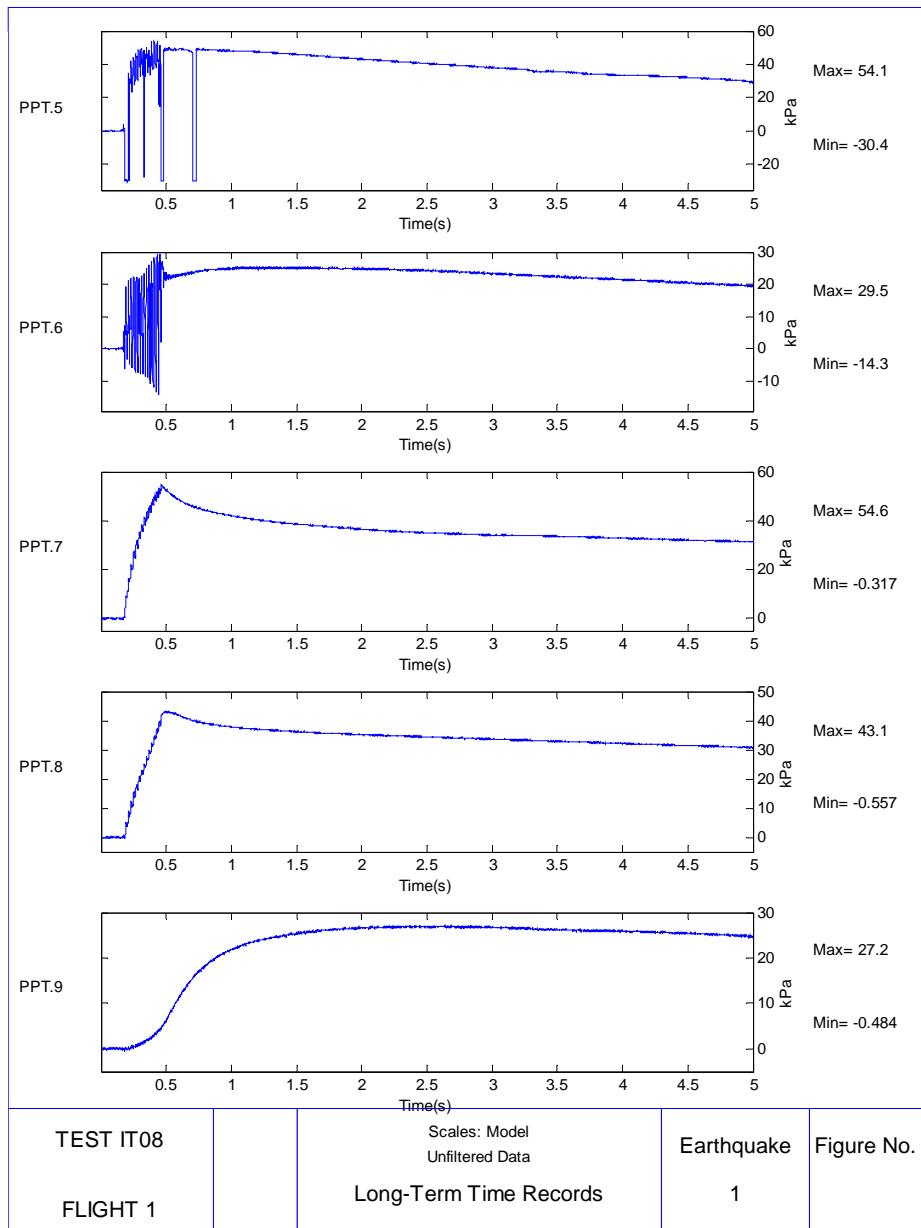
### 2.3.1 IT08, Earthquake 1



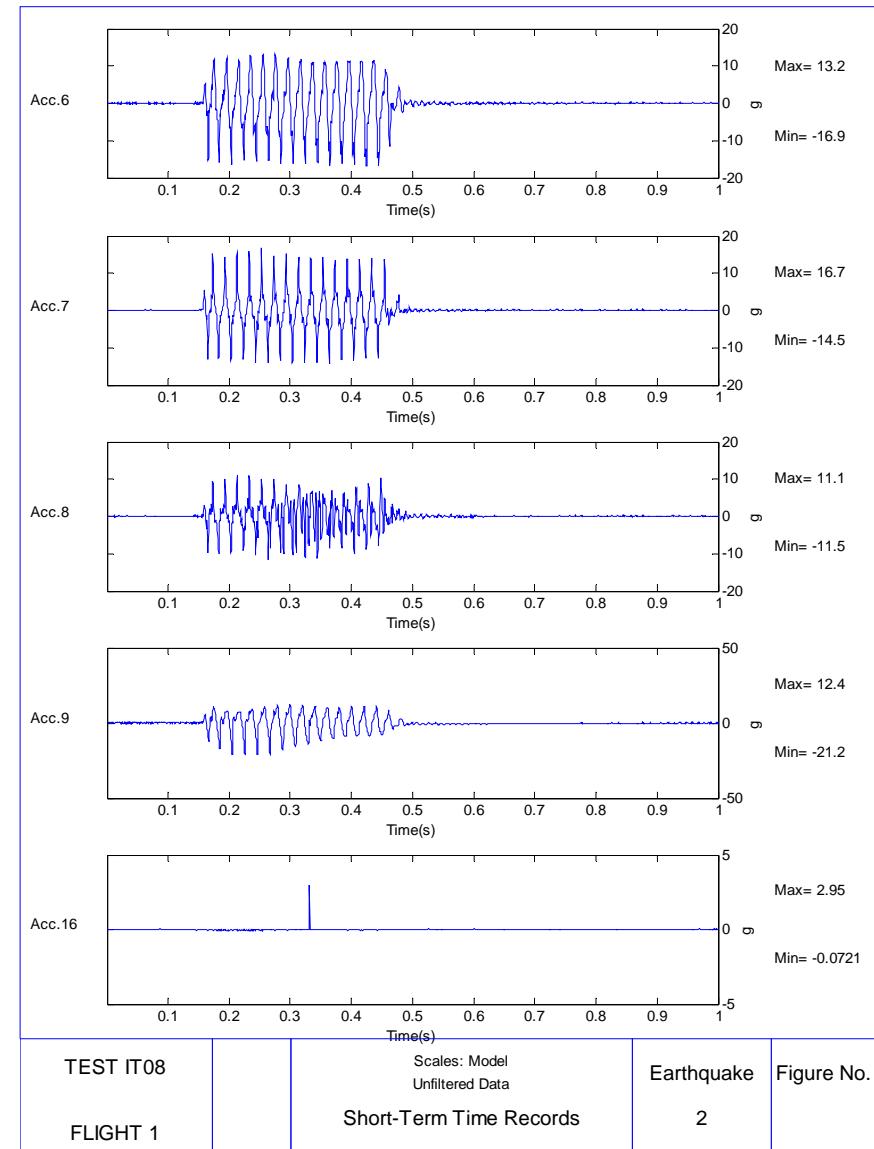
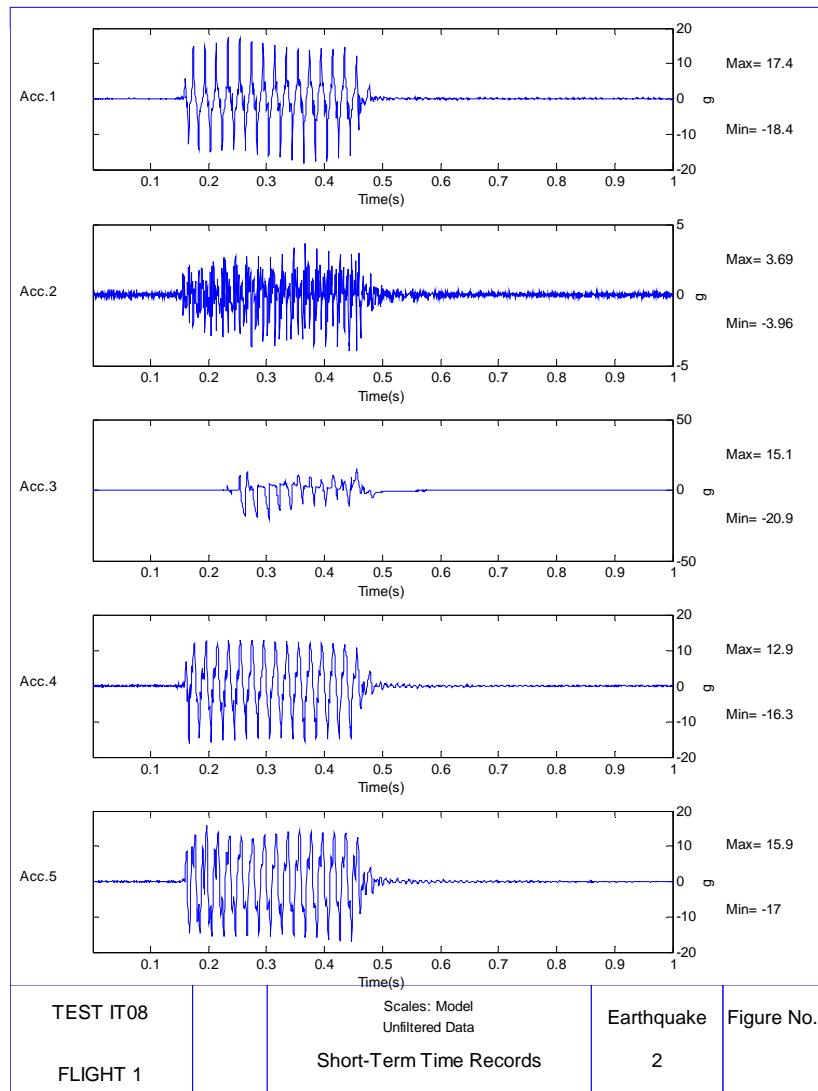
# CUED/D-SOILS/TR339



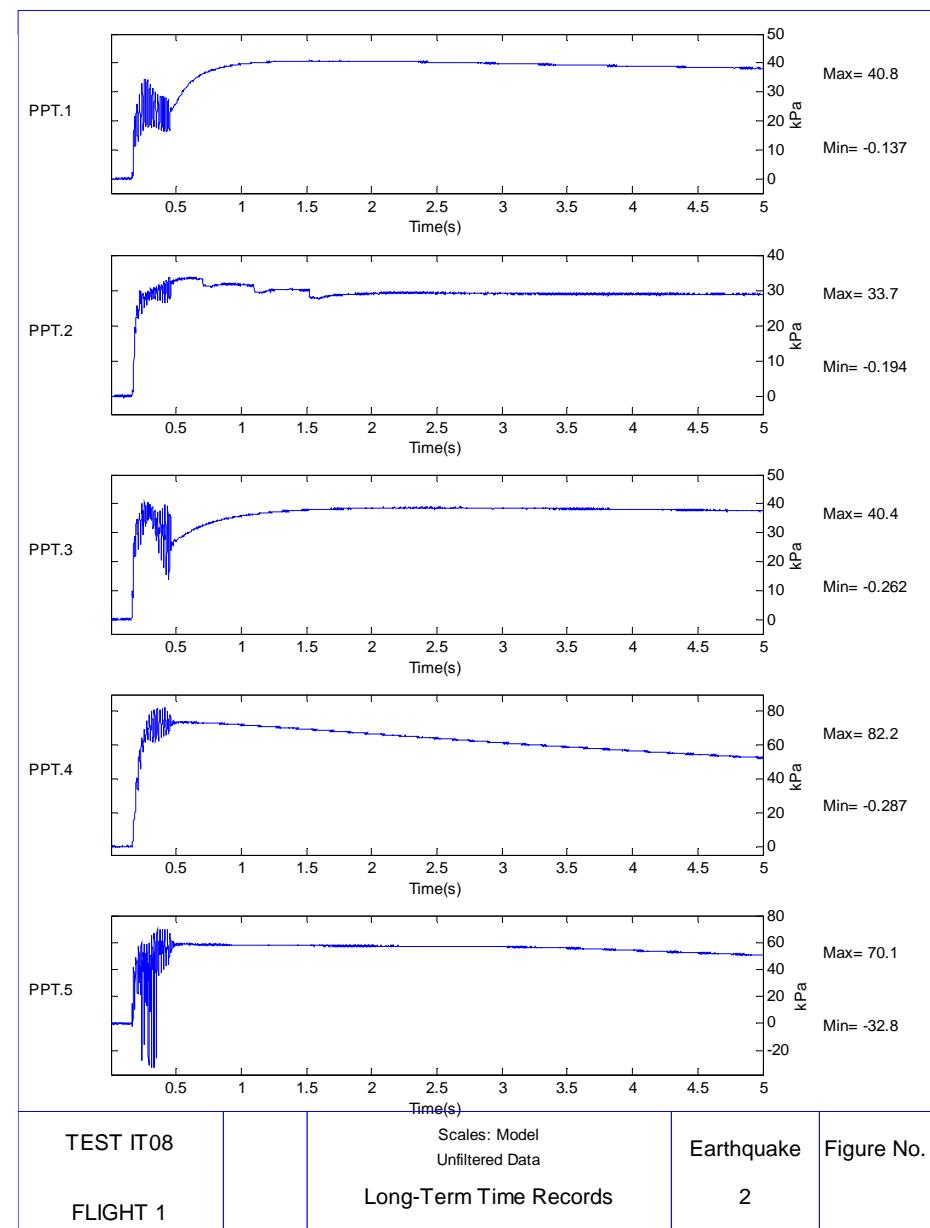
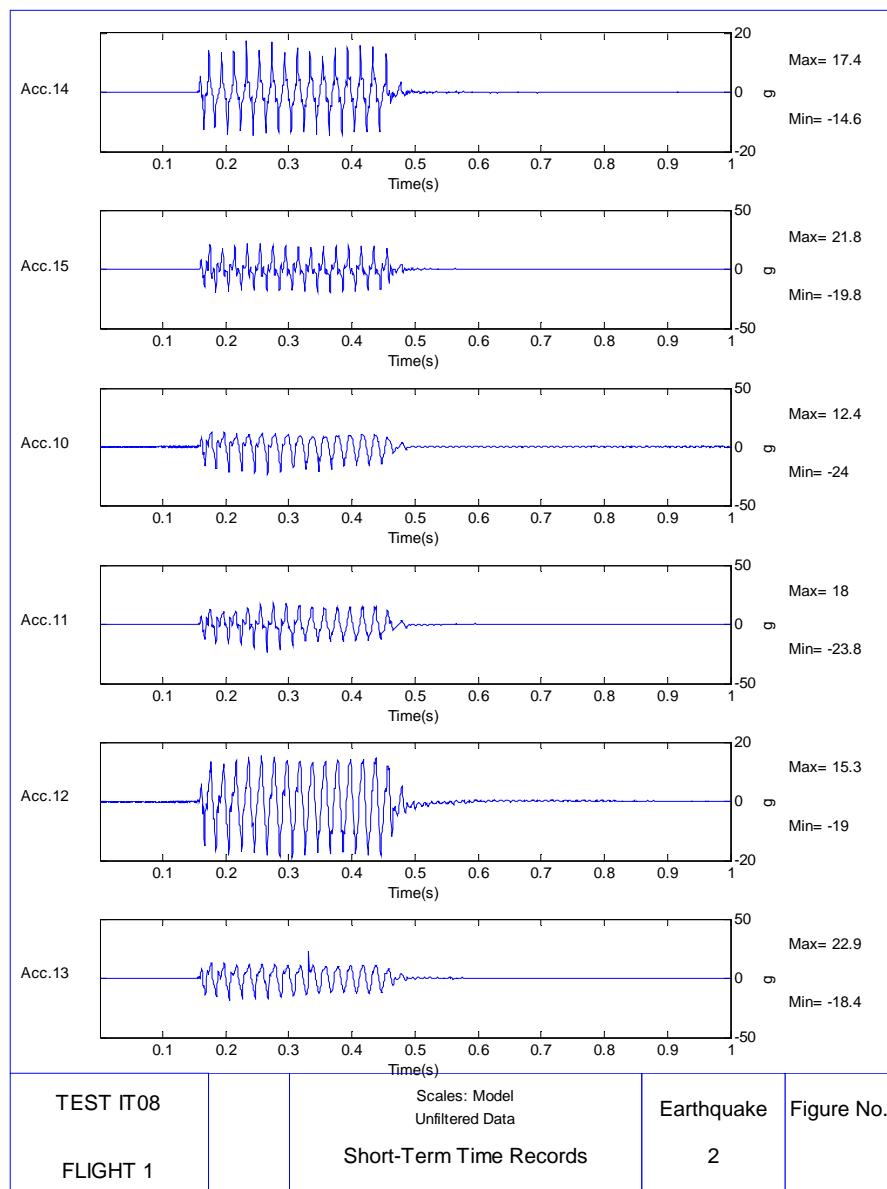
# CUED/D-SOILS/TR339



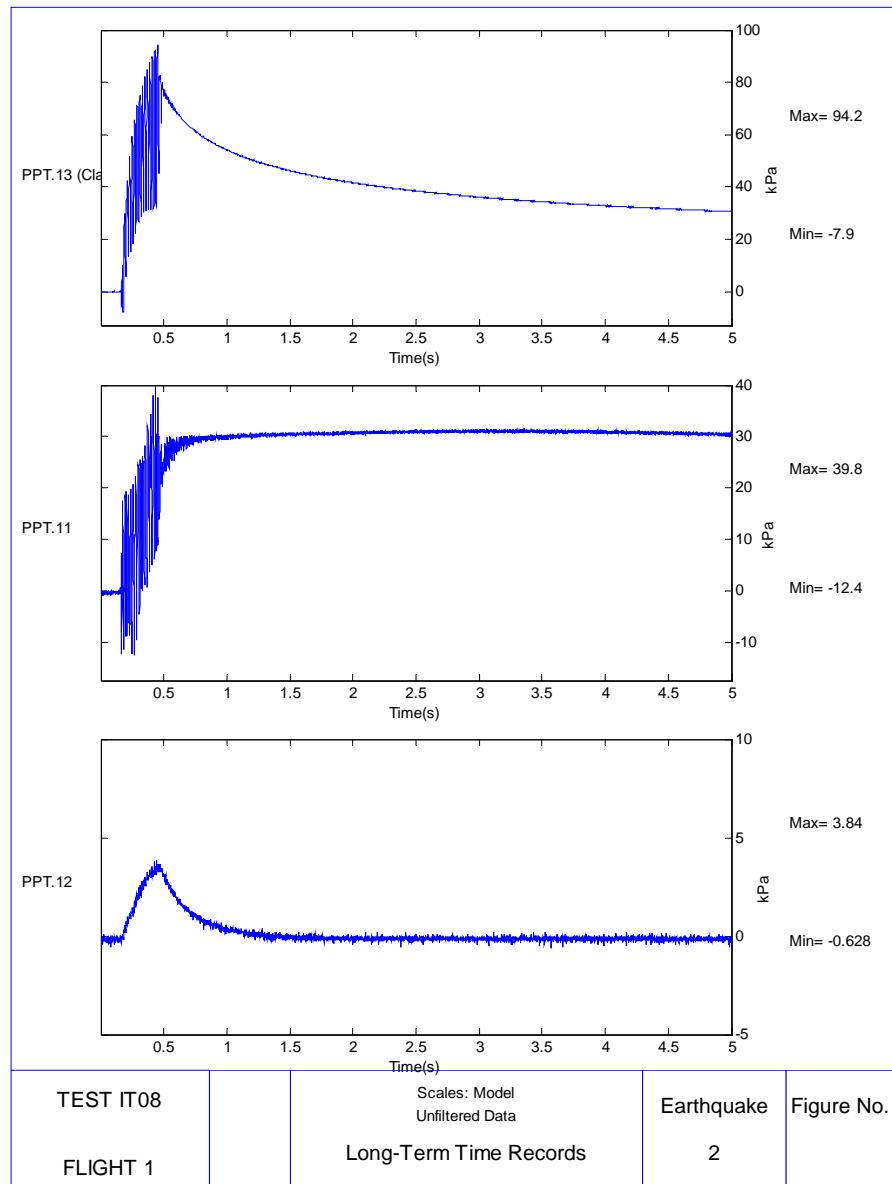
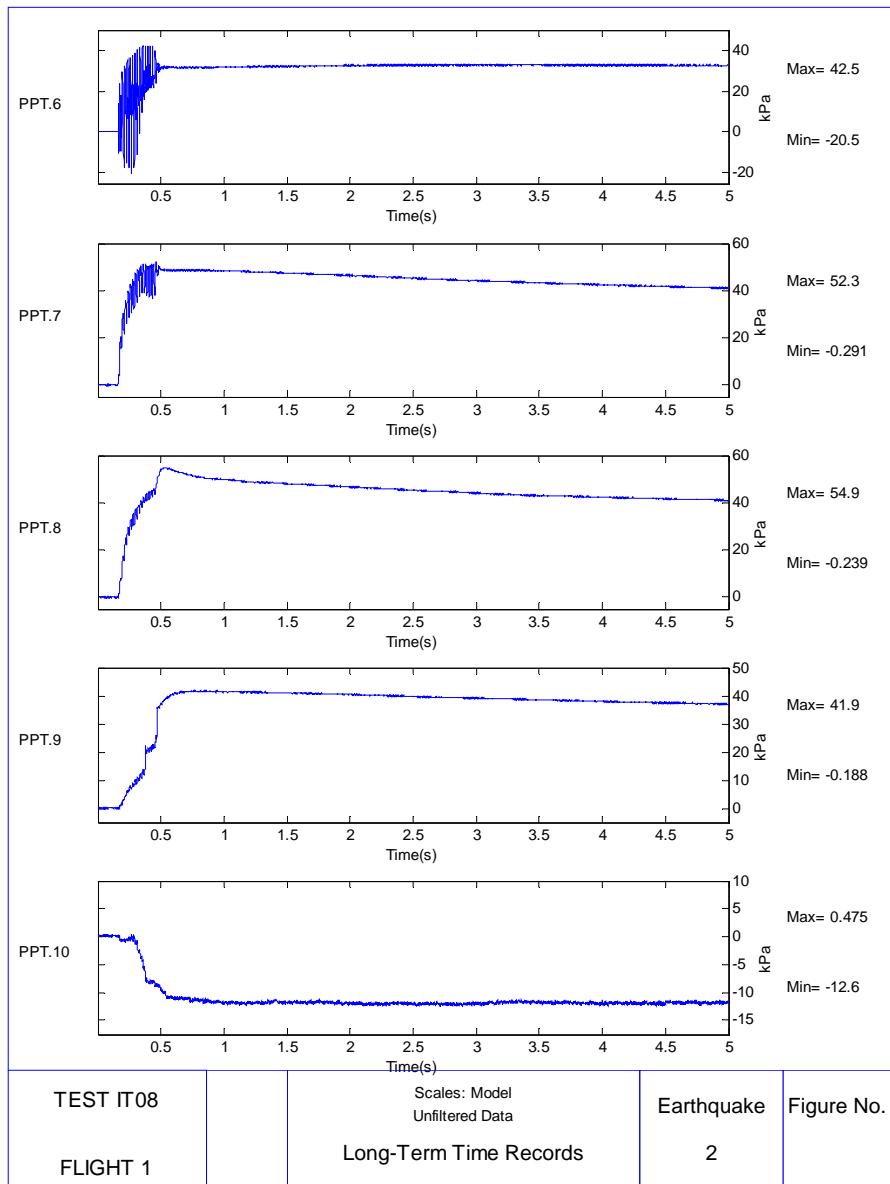
## 2.3.2 IT08, Earthquake 2



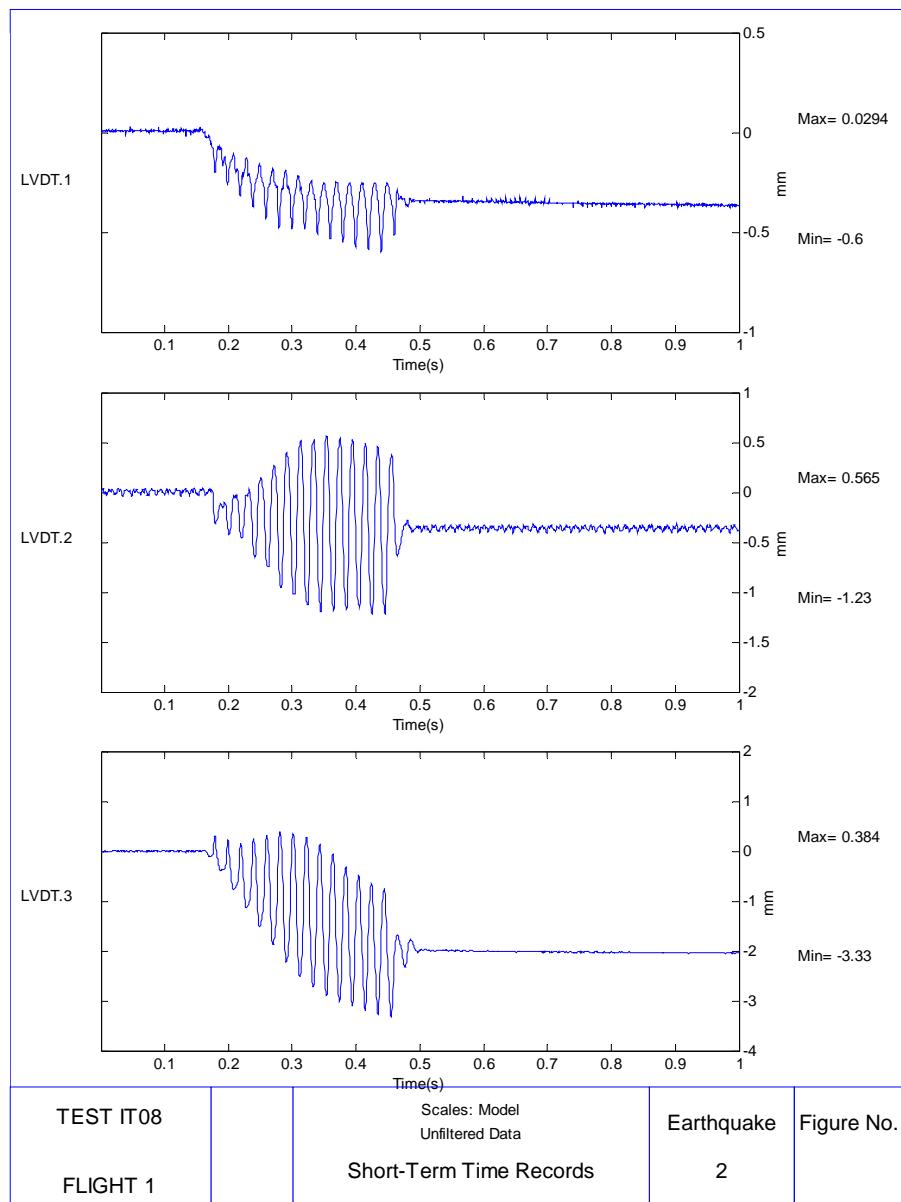
# CUED/D-SOILS/TR339



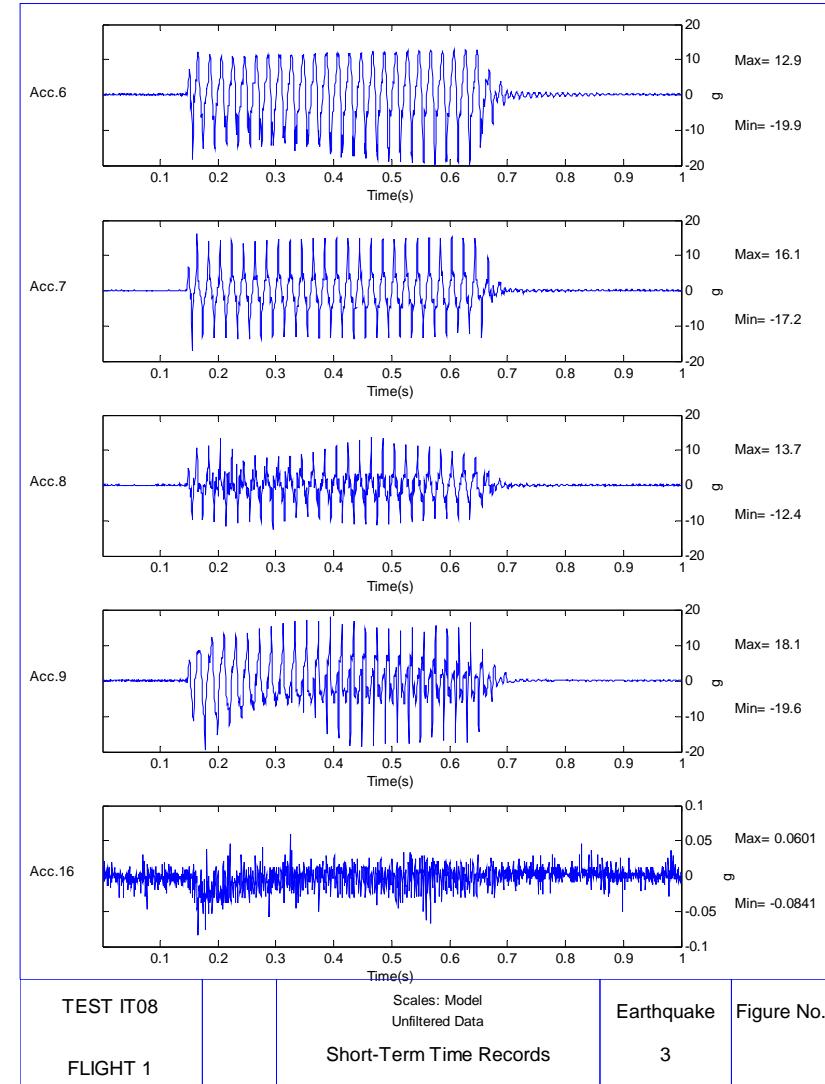
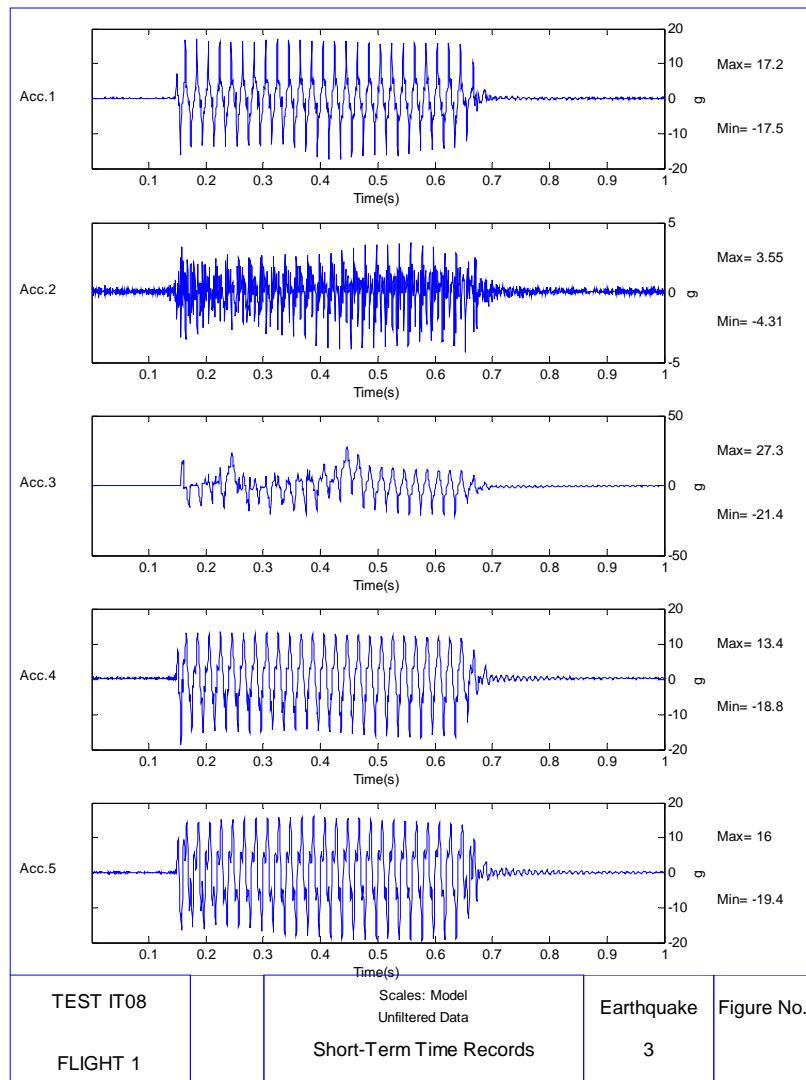
# CUED/D-SOILS/TR339



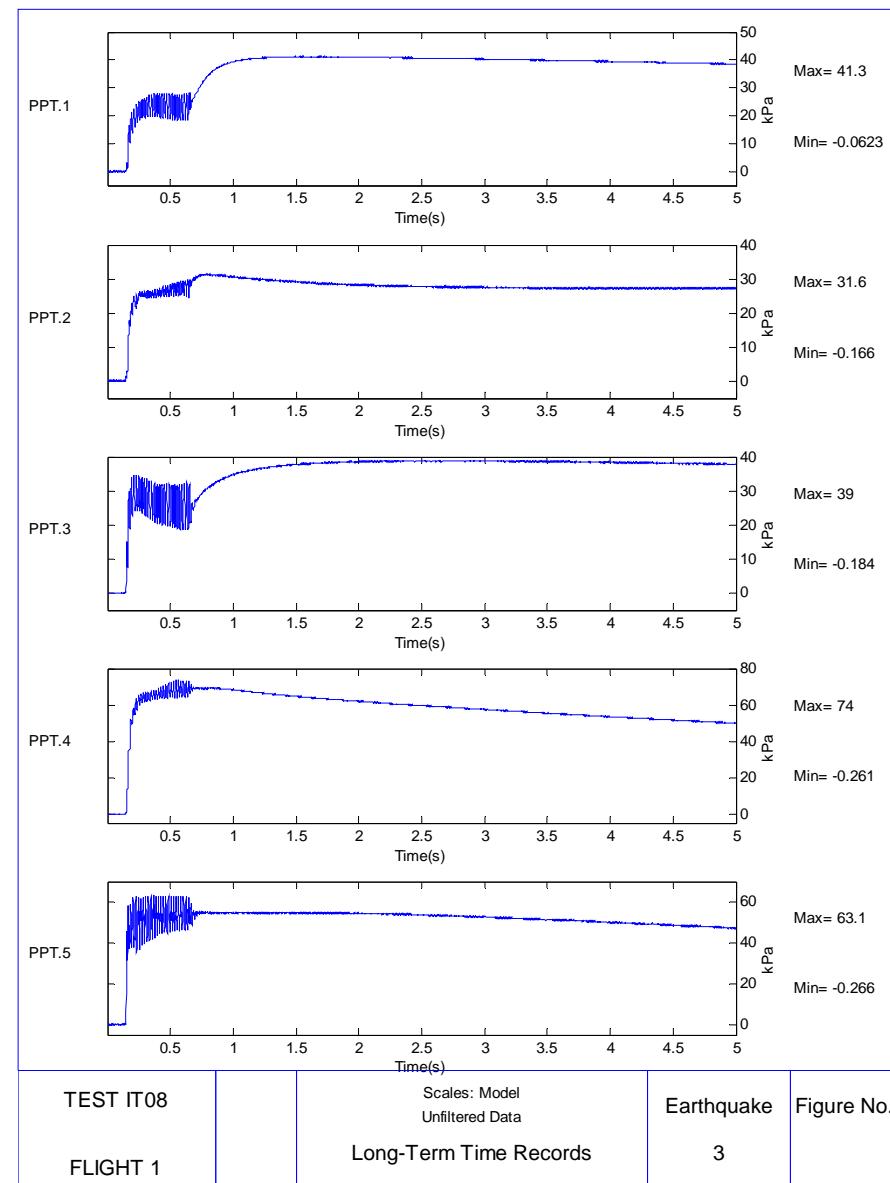
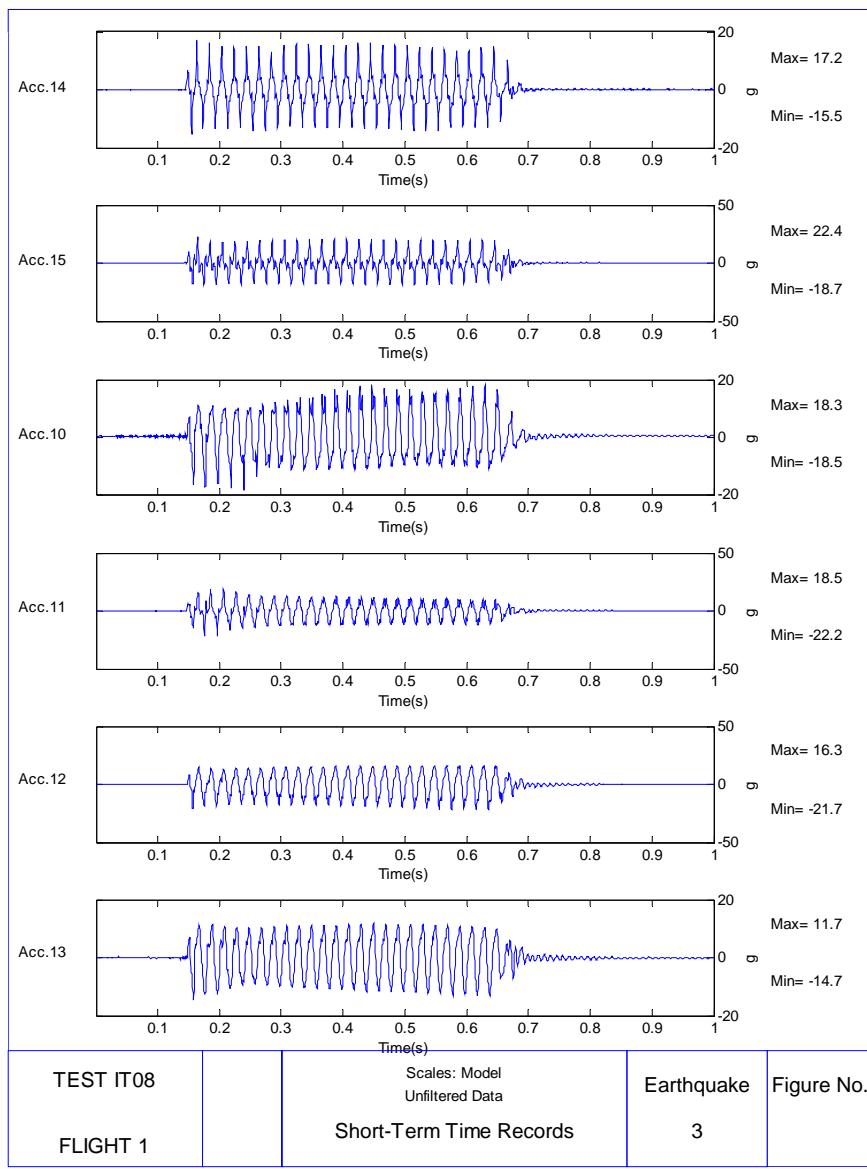
CUED/D-SOILS/TR339



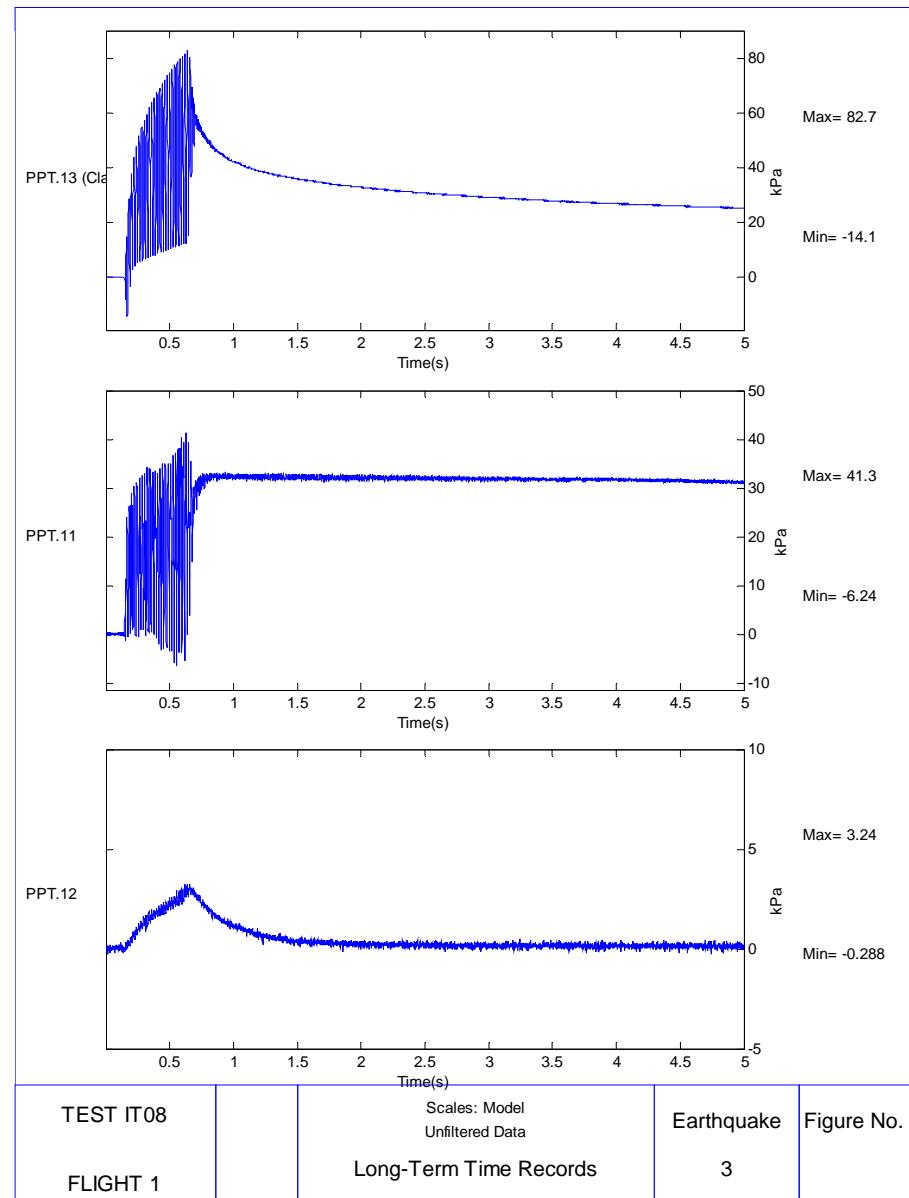
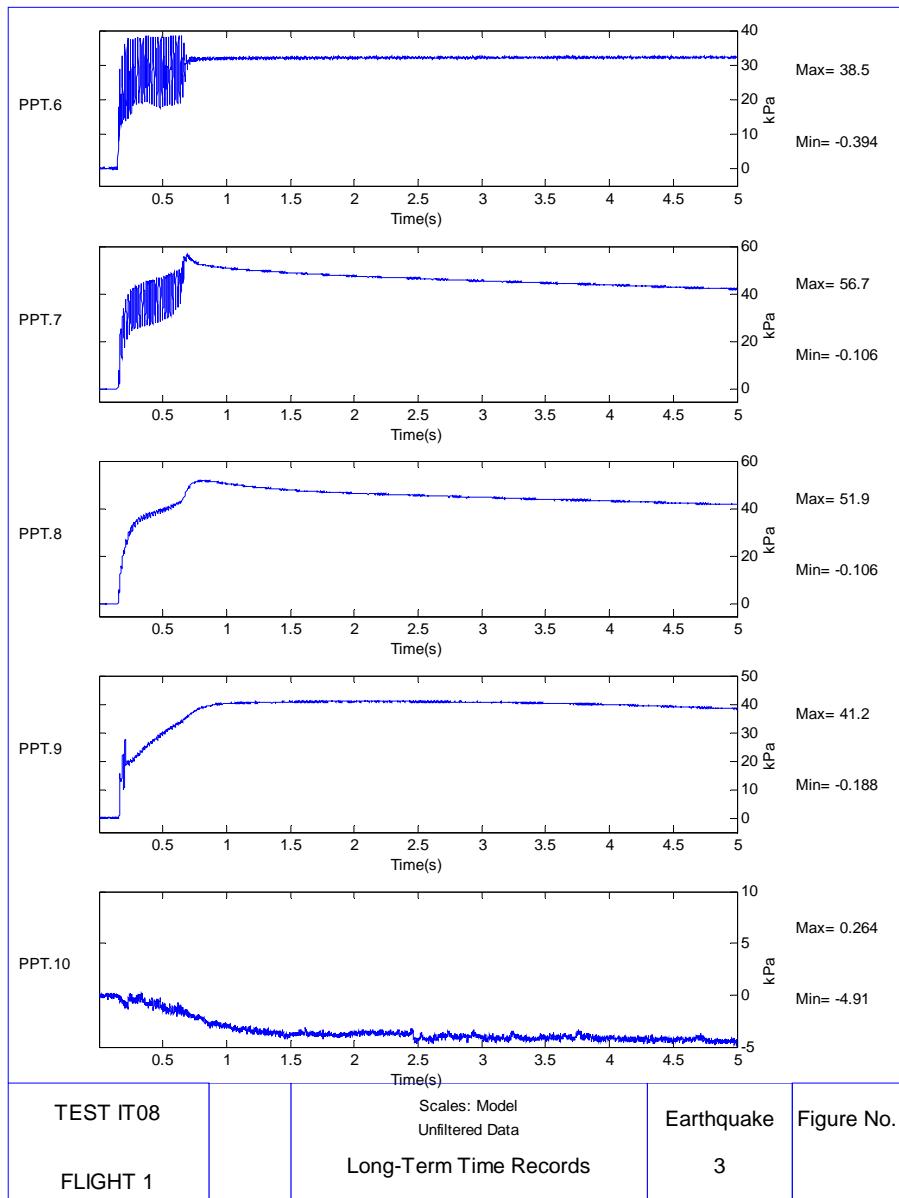
## 2.3.3 IT08, Earthquake 3



# CUED/D-SOILS/TR339



# CUED/D-SOILS/TR339



CUED/D-SOILS/TR339

