Tensile behaviour of geomembrane on landfill slopes - Data report on centrifuge tests IT04 and IT06

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1. Introduction

Geomembranes placed on side slopes of a landfill can experience tension due to various factors. For example, during construction of the liner systems, wind up-lift on uncovered areas, movement of heavy vehicles such as bulldozers and frictional forces from the cover soil can all cause tension in the geomembrane. After the closure of a landfill, the down-drag caused by settling waste also induces tension in the geomembrane. For landfills located in seismic regions, the most critical loading to the liner system and geomembrane may be expected during an earthquake. Earthquake loading induces tension in the geomembrane in addition to the tension it experiences from the down-drag of settling waste. Geomembranes are commonly anchored at the crest level of each bench, hence an increased geomembrane tension can lead to geomembrane slippage/failure, anchor failure or liner system instability. Any of these events can impair the functionality of the liner and cause leakage of leachate leading to ground water pollution or a catastrophic failure of landfill. Hence it is important to understand both the static and seismic performance of geomembranes in landfill liner systems.

This data report presents results from dynamic centrifuge tests IT04 and IT06 which modelled

1. A completed landfill with a single geomembrane-clay liner system with 45° side slope and 7 m deep waste (**Fig.1**) and
2. A landfill cell, with a single geomembrane-clay liner system with 45° side slope, 40° waste slope and 7 m deep waste (**Fig. 2**).

The landfills modelled in the dynamic centrifuge test were municipal solid waste (MSW) landfills with prototype slope length 9.9 m. The tension in the model geomembrane was measured while the geomembrane was subjected to static loading by the weight of the model waste and by earthquake loadings of varying intensity, frequency and duration.

Detailed analysis of the data provided in this report is given in Thusyanthan (2005)- Ph.D thesis, University of Cambridge, UK.

2. Model preparation IT04 & IT06

2.1. Model IT04

The schematic cross section of the centrifuge model is shown in **Fig.1**. The model was prepared in a equivalent shear beam box (ESB) of internal dimensions 235 mm × 560 mm × 222 mm as described in section 3.7 in chapter 3. The top edge of the model geomembrane was clamped and attached to a load cell. A metal support was used to guide the clamp in the slope direction.

Pressure sensors need to be placed on the side slope of the geomembrane in such a way that it does not affect the tension induced in the geomembrane and the pressure sensors do not experience the shear stress that rises as the model waste moves down. This was achieved by gluing the pressure sensors behind a strip of model geomembrane, and pasting the strip to the top of the geomembrane on the slope. This arrangement enabled the measurement of both the geomembrane tension and the normal pressure on the side slope.

The model waste was placed into the landfill, on top of the model geomembrane, in layers; each layer was compacted by static load to produce a unit weight of 9 kN/m^3. Linearly variable displacement transducers (LVDT) were mounted on the top of the container to measure the model waste settlement during swing up and during earthquake loading. The slope length in prototype scale is 9.9 m.

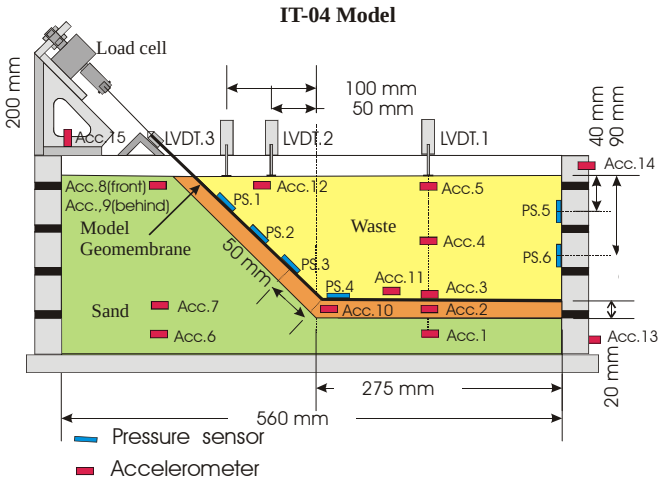


Fig.1 Schematic cross section of centrifuge model IT04.

2.2. Model IT06

A schematic cross section of the centrifuge model is shown in **Fig. 2**. The model preparation was similar to model IT04 described in the above section. Firstly, fraction-E dry silica sand was air pluviated to a depth of 200 mm (relative density 45%). Accelerometers were placed at the locations shown in **Fig. 2** during the sand pouring stage. The sand was then saturated with water, drained and excavated to obtain the 45° slope. The 2 cm thick clay strips were placed on the base and the side slope of the excavation. Model geomembrane was placed on top of the clay liner and attached to the clamp and the load cell. The model waste was then placed into the model in layers, creating a 40° slope. Each layer was compacted by static load to produce a unit weight of 9 kN/m^3. Linearly variable displacement transducers (LVDT) were mounted as shown in **Fig. 2** to measure the model waste settlement while the centrifuge was being accelerated, and during earthquake loading.

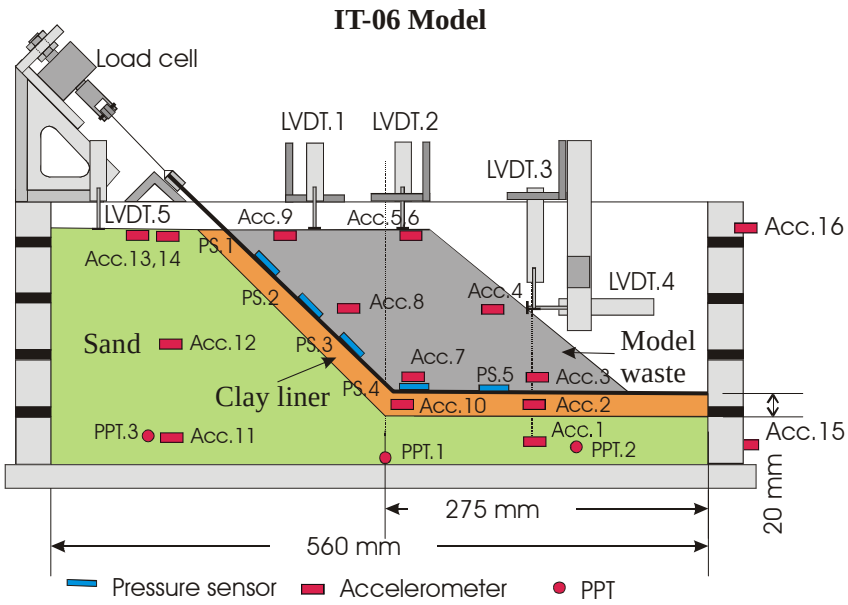


Fig. 2 Schematic cross section of centrifuge model IT06.

3. Testing Procedure

Testing procedure was similar for both IT04 and IT06 tests. Completed model was loaded into the centrifuge. A pre-tension of about 10N was applied to the model geomembrane by tightening the load cell fitting. This pretension is required to remove any slag in the geomembrane and clamp attachment to load cell. The model was swung up to 50g in stages of 10g (i.e. 10g, 20g, 30g, 40g and 50g). Load cell, LVDT and pressure cell measurements were all recorded throughout the swing up. Once the consolidation of waste had finished at 50g,

earthquakes of varying intensity and magnitude were fired using the Stored Angular Momentum (SAM) earthquake actuator, Madabhushi et al. (1998). **Table.1** and **Table.2** provide the details of the fired model earthquakes in test IT04 and IT06 respectively. Enough time (10 to 20 minutes) was allowed between the model earthquakes for the geomembrane and instruments to reach equilibrium.

Table.1 Simulated earthquakes in test IT04, prototype scale [model scale].

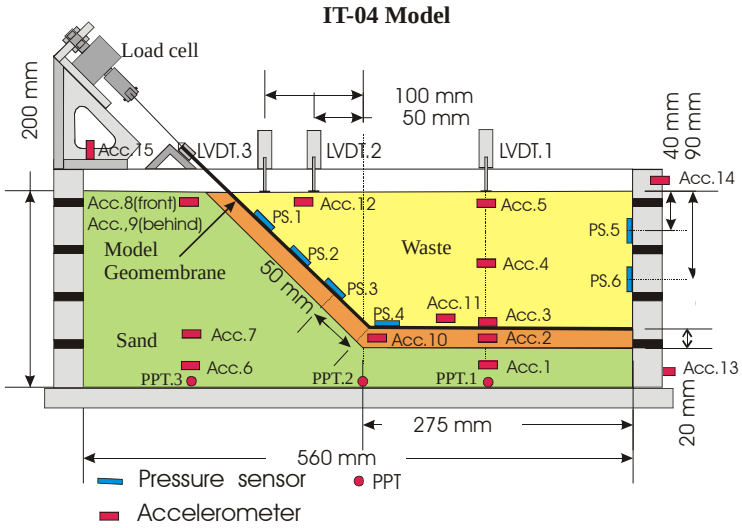
Model Earthquake Number	Driving Frequency (Hz)	Duration (s)	Maximum base acceleration-Acc.1(g)	Average of Max. base acceleration at Acc.1(g)
E.1	0.6 [30]	15 [0.3]	0.091 [4.55]	0.080 [4.00]
E.2	0.8 [40]	15 [0.3]	0.126 [6.30]	0.100 [5.00]
E.3	1 [50]	15 [0.3]	0.214 [10.70]	0.125 [6.25]
E.4	1 [50]	15 [0.3]	0.184 [9.20]	0.110 [5.50]
E.5	1 [50]	15 [0.3]	0.252 [12.60]	0.160 [8.00]
E.6	1 [50]	25 [0.5]	0.310 [15.50]	0.210 [10.50]
E.7	1 [50]	15 [0.3]	0.320 [16.00]	0.225 [11.25]

Table.2 Simulated earthquake loading in test IT06, prototype scale [model scale].

Model Earthquake Number	Driving frequency (Hz)	Duration (s)	Maximum base acceleration-Acc.1(g)	Average of Max. base acceleration at Acc.1(g)
E.1	0.6 [30]	15 [0.3]	0.065 [3.25]	0.050 [2.50]
E.2	0.8 [40]	15 [0.3]	0.122 [6.10]	0.100 [5.00]
E.3	1 [50]	15 [0.3]	0.194 [9.70]	0.125 [6.25]
E.4	1 [50]	15 [0.3]	0.160 [8.00]	0.150 [7.50]
E.5	1 [50]	15 [0.3]	0.250 [12.5]	0.190 [9.50]
E.6	1 [50]	25 [0.5]	0.246 [12.3]	0.210 [10.50]

4. Centrifuge data acquisition setup

IT-04

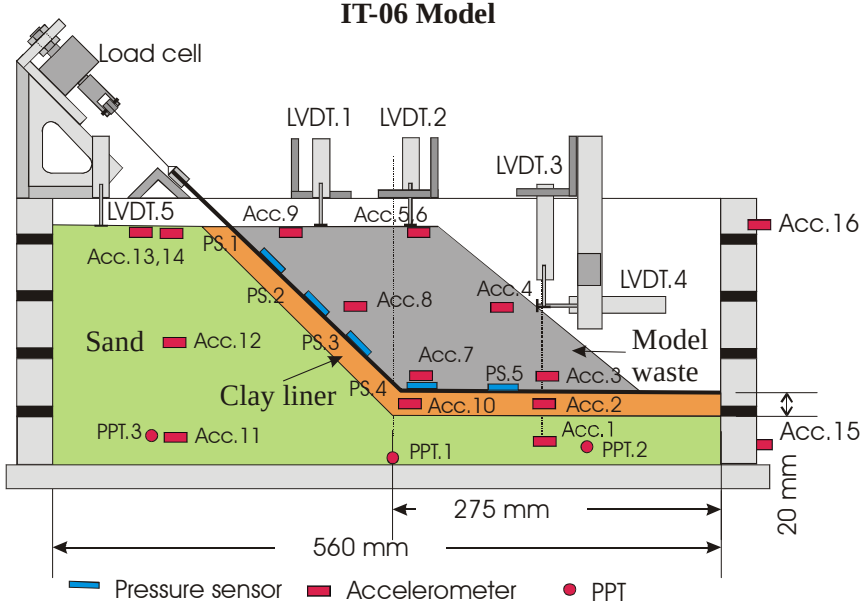


Test IT04 Date :- 24/09/2003

Junction Box	Instrument Type	Number	Factor	Units	x (mm)	y (mm)	z (mm)
1	Acc.15 (Vertical)	7340	7.584	g/V	0	0	-20
2	Acc.14	3477	8.403	g/V	560	0	-10
3	SAM clutch	-	7.000	g/V		0	
4	Acc.1	9889	8.811	g/V	410	0	180
5	Acc.2	8113	5.102	g/V	410	0	150
6	Acc.3	8077	9.091	g/V	410	0	135
7	Acc.4	8925	7.072	g/V	410	0	80
8	Acc.5	8076	8.264	g/V	410	0	37

9	Acc.6	8116	5.571	g/V	110	0	182
10	Acc.7	8112	5.536	g/V	110	0	150
11	Acc.8	8895	7.326	g/V	110	0	20
12	Acc.9	8915	7.246	g/V	110	0	21
13	Acc.10	8830	6.993	g/V	285	0	150
14	Acc.11	8131	7.446	g/V	325	0	135
15	Acc.12	8932	7.143	g/V	225	0	20
16	Acc.13 (Box base)	9882	8.929	g/V	560	0	180
17	Load cell		-200.02	N/V		0	
18	LVDT.1	9154	-3.669	mm/V	410	0	0
19	LVDT.2	9181	-3.560	mm/V	235	0	0
20	LVDT.3	9003	-3.587	mm/V	185	0	0
21	non			-		0	
22	PS.1	D35	51.462	kPa/V	185	0	30
23	PS.2	D34	52.400	kPa/V	220	0	60
24	PS.3	D28	269.850	kPa/V	255	0	100
25	PS.4	D32	235.980	kPa/V	310	0	135
26	PS.5	D24	46.165	kPa/V	560	0	40
27	PS.6	D27	50.493	kPa/V	560	0	90
28	PPT.1	10863	85.916	kPa/V	410	0	200
29	PPT.2	6675	83.003	kPa/V	285	0	200
30	PPT.3	10864	87.108	kPa/V	110	0	200

IT-06 Model

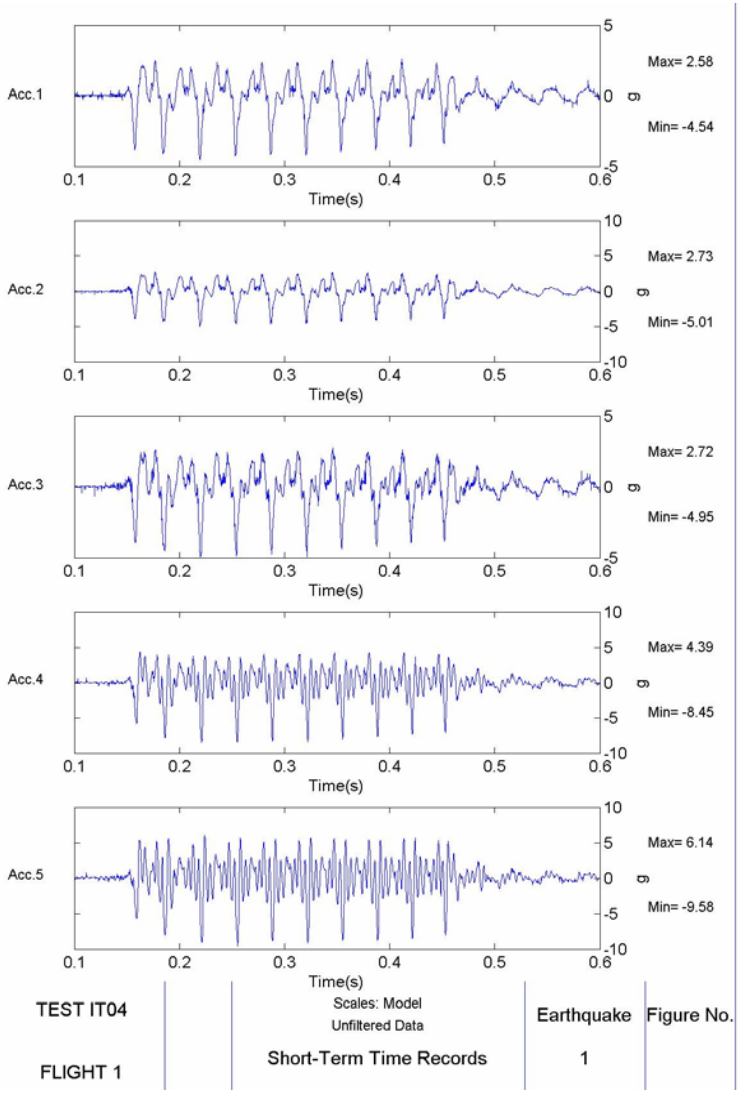


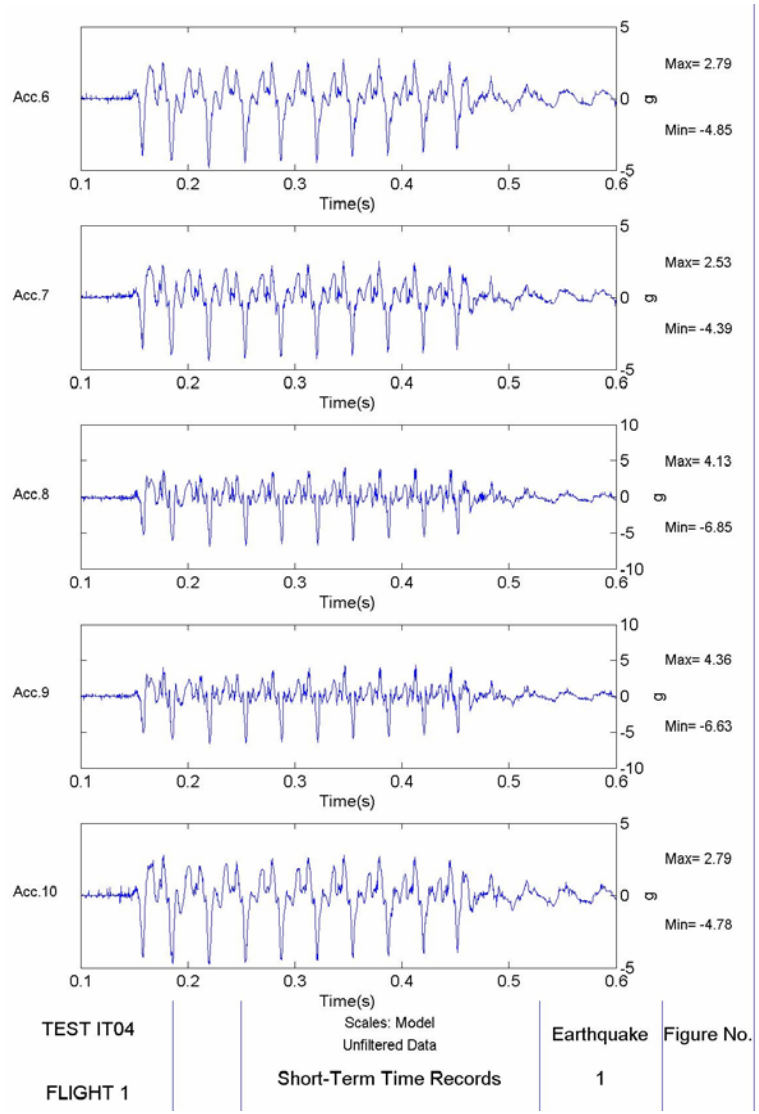
Test	IT06	Date	18/12/2003				
Junction Box	**Instrument Type**	**Number**	**Factor**	**Units**	**x (mm)**	**y (mm)**	**z (mm)**
1	Load cell		-200.020	N/V			
2	LVDT.5	M241-14	3.590	mm/V			
3	LVDT.1	M241-15	3.550	mm/V			
4	LVDT.2	M241-03	3.520	mm/V			
5	LVDT.3	M241-18	3.510	mm/V			
6	PS.1	D34	51.909	kPa/V			
7	PS.2	D24	45.532	kPa/V			

8	PS.3	D27	49.846	kPa/V			
9	PS.4	D26	47.452	kPa/V			
10	PS.5	D32	253.260	kPa/V			
11	LVDT.4	LVDT3	3.669	mm/V			
12	Laser	Laser	-31.389	mm/V			
13	PPT.1	6803	87.272	kPa/V	285	0	200
14	PPT.2	6674	87.160	kPa/V	485	0	190
15	PPT.3	6783	89.880	kPa/V	150	0	190
16	non		0.000				
17	Acc.15	8077	9.005	g/V			
18	Acc.16	7698	7.000	g/V			
19	Acc.1	9882	8.715	g/V	410	0	180
20	Acc.2	8116	5.389	g/V	410	0	150
21	Acc.3	9889	8.905	g/V	425	0	130
22	Acc.4	7340	7.446	g/V	385	0	73
23	Acc.5	8925	7.584	g/V	325	0	20
24	Acc.6	8131	7.249	g/V	320	0	20
25	Acc.7	8915	6.770	g/V	320	0	126
26	Acc.8	8932	7.315	g/V	250	0	73
27	Acc.9	8112	5.285	g/V	200	0	23
28	Acc.10	8113	5.057	g/V	315	0	150
29	Acc.11	1926	6.660	g/V	80	0	180
30	Acc.12	7427	8.985	g/V	80	0	100
31	Acc.13	728	19.047	g/V	80	0	20
32	Acc.14	3477	8.110	g/V	70	0	20

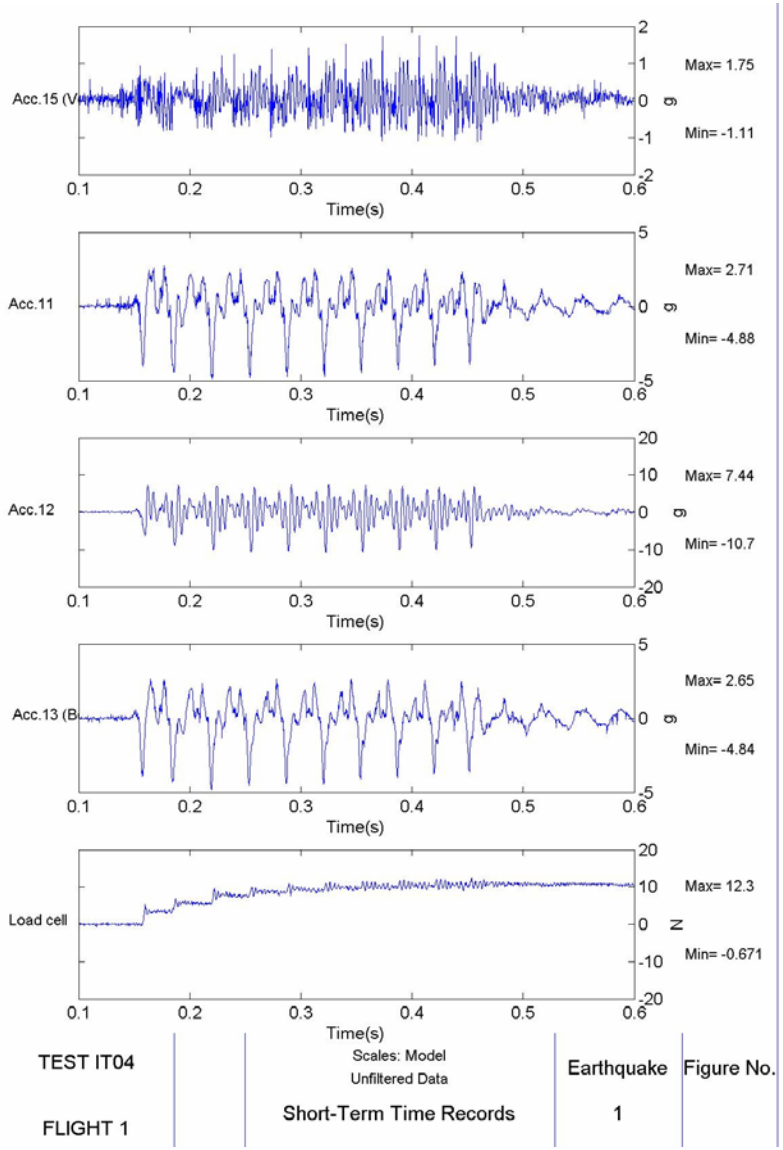
5. Results

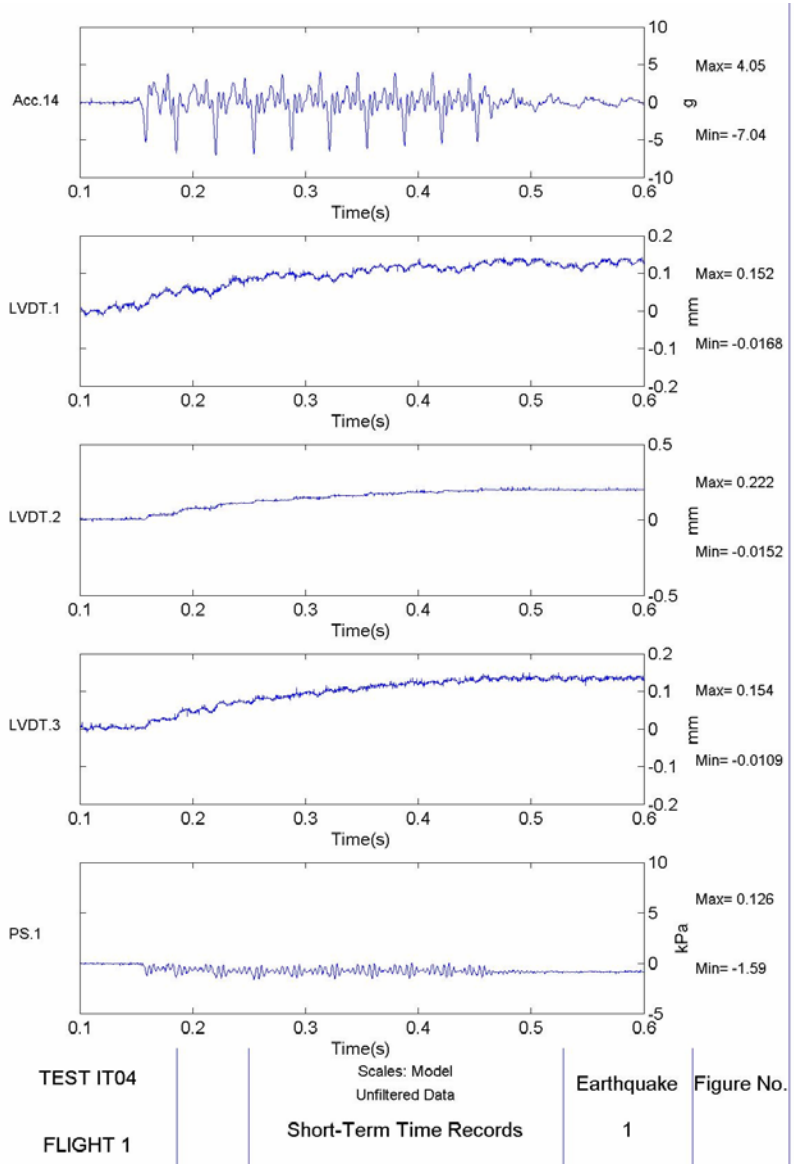
1. Data from Test IT04, Earthquake 1.



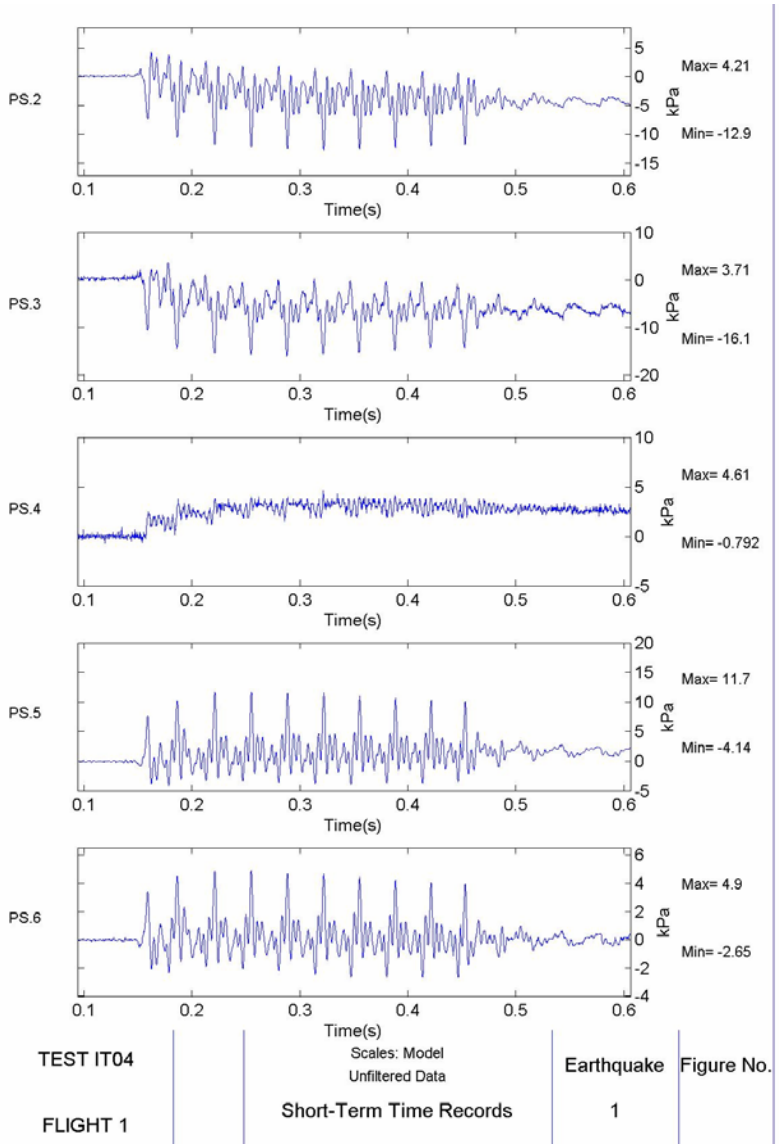


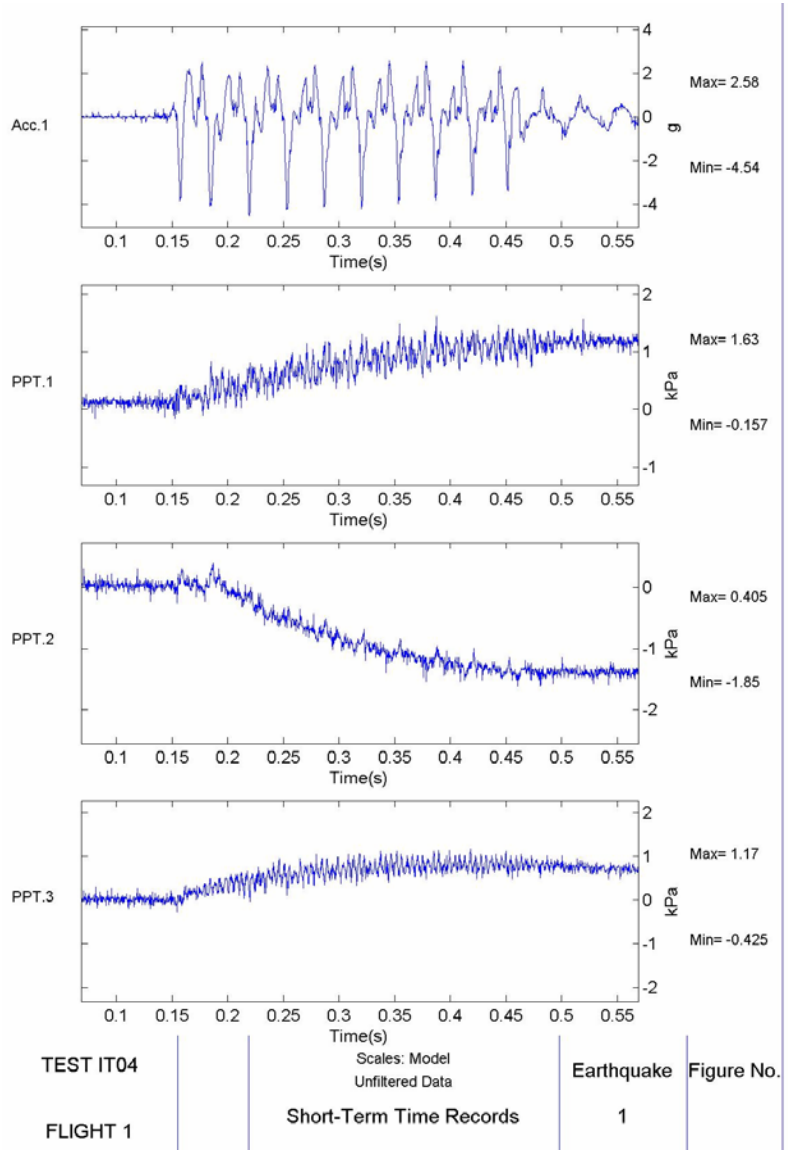
2. Data from Test IT04, Earthquake 1.


Acc.15 (V
Max= 1.75
Min= -1.11
Acc.11
Max= 2.71
Min= -4.88
Acc.12
Max= 7.44
Min= -10.7
Acc.13 (B
Max= 2.65
Min= -4.84
Load cell
Max= 12.3
Min= -0.671
Time(s)
g
N
TEST IT04
FLIGHT 1
Scales: Model
Unfiltered Data
Short-Term Time Records
Earthquake
1
Figure No.

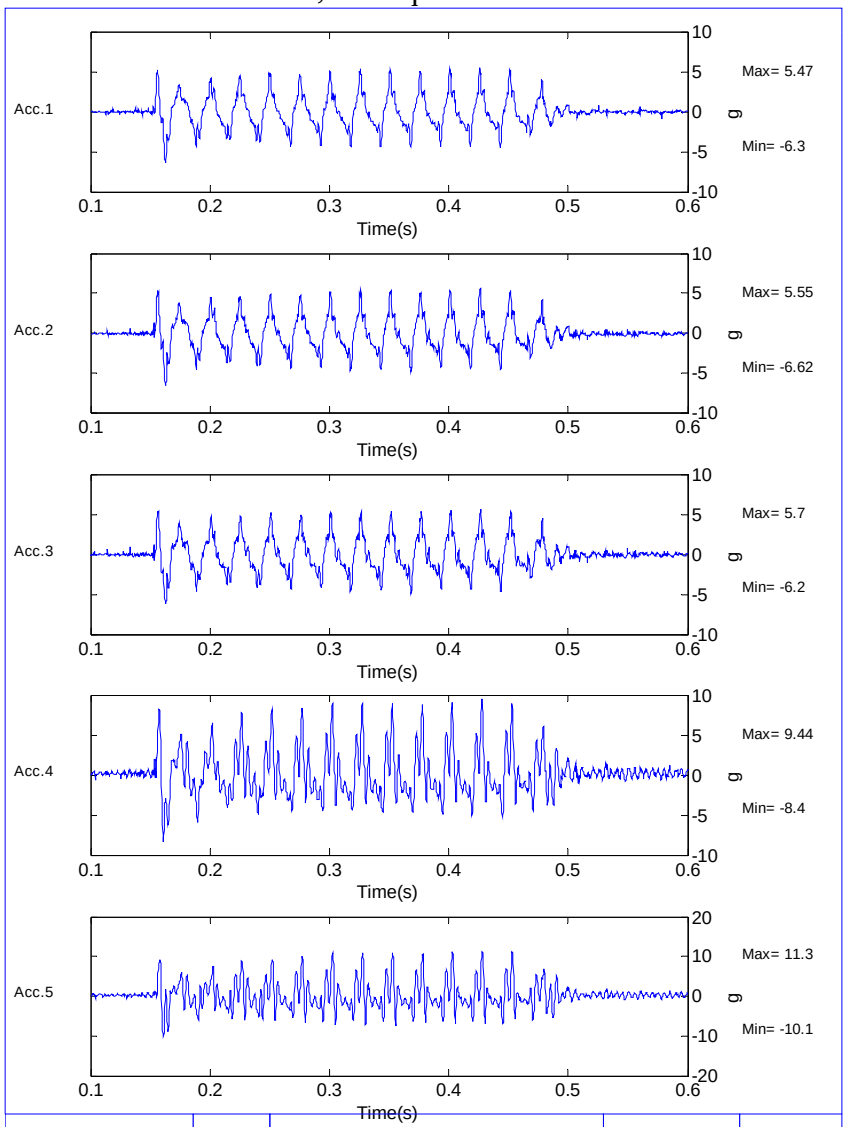

Acc.14
Max= 4.05
Min= -7.04
LVDT.1
Max= 0.152
Min= -0.0168
LVDT.2
Max= 0.222
Min= -0.0152
LVDT.3
Max= 0.154
Min= -0.0109
PS.1
Max= 0.126
Min= -1.59
Time(s)
g
mm
kPa
TEST IT04
FLIGHT 1
Scales: Model
Unfiltered Data
Short-Term Time Records
Earthquake
1
Figure No.

3. Data from Test IT04, Earthquake 1.

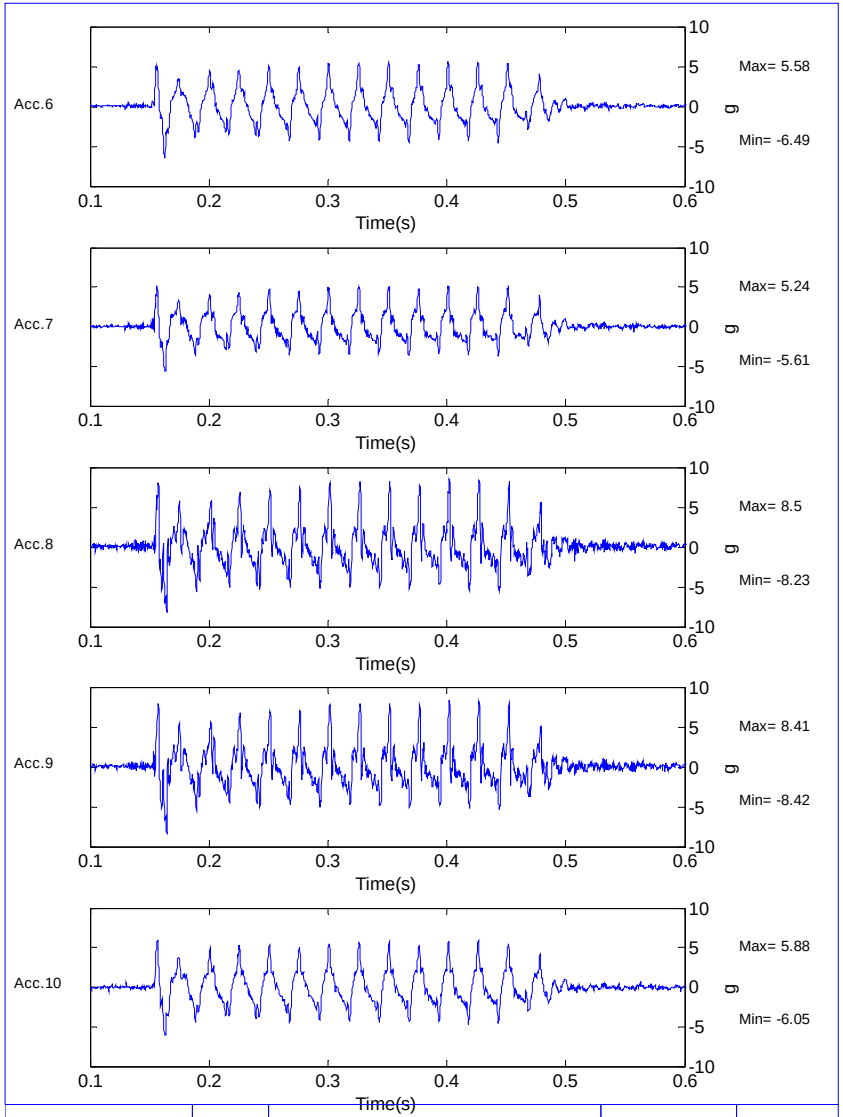




4. Data from Test IT04, Earthquake 2.

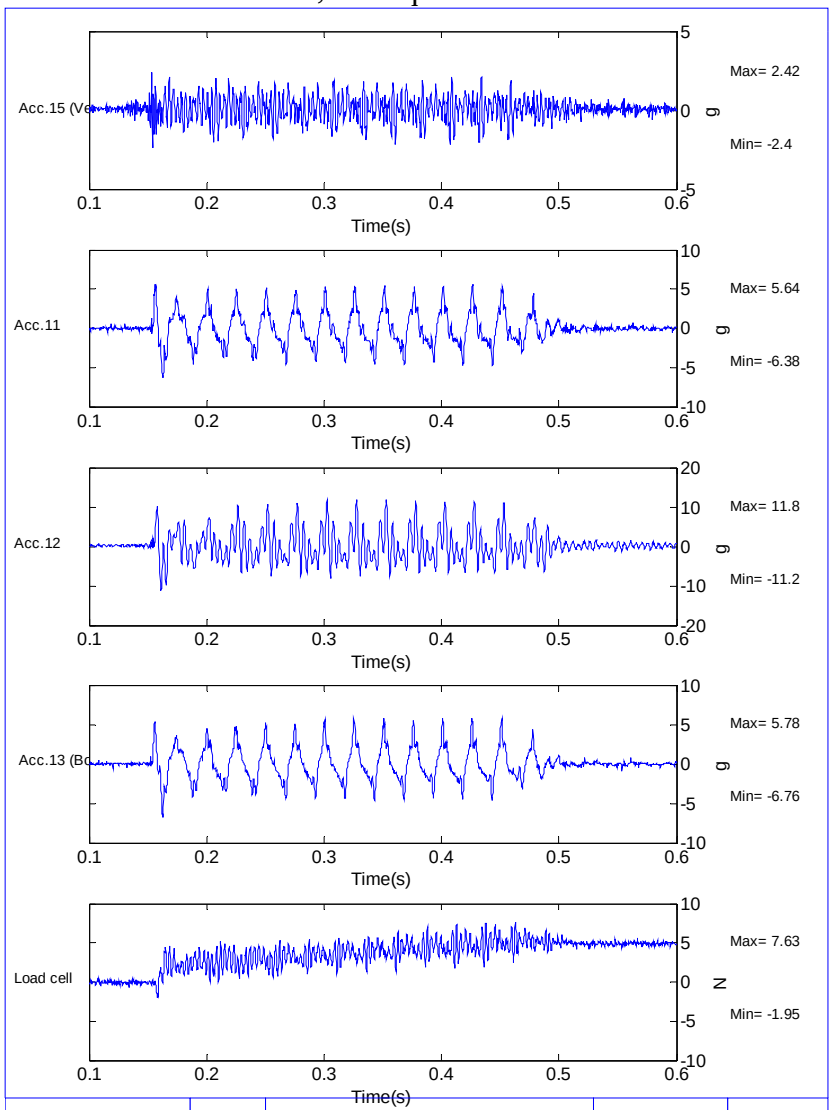


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 2	Figure No.

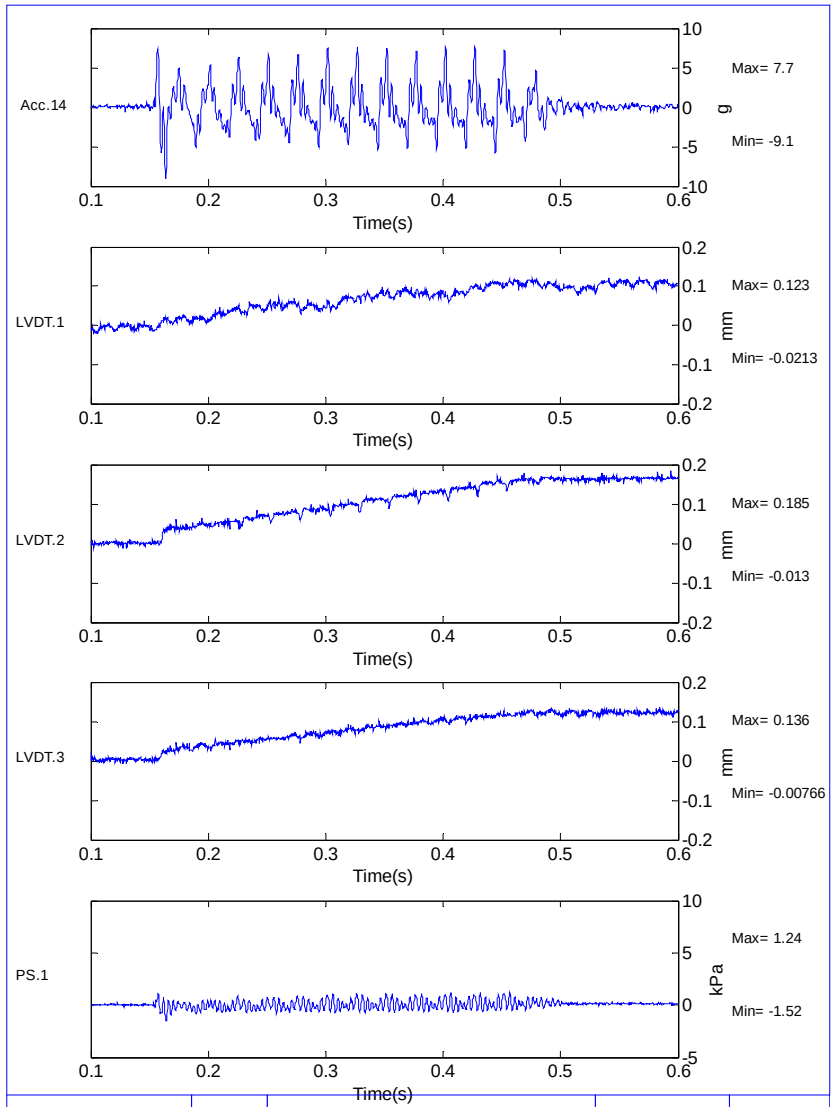


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 2	Figure No.

5. Data from Test IT04, Earthquake 2.

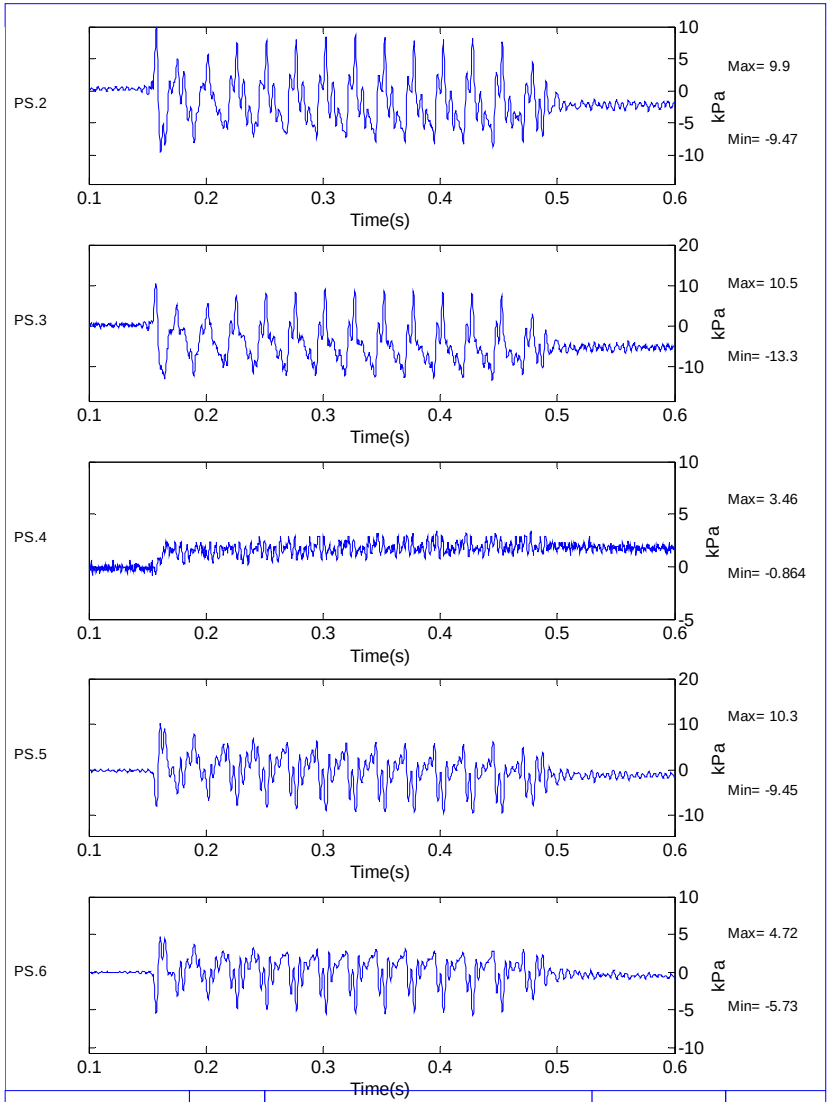


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

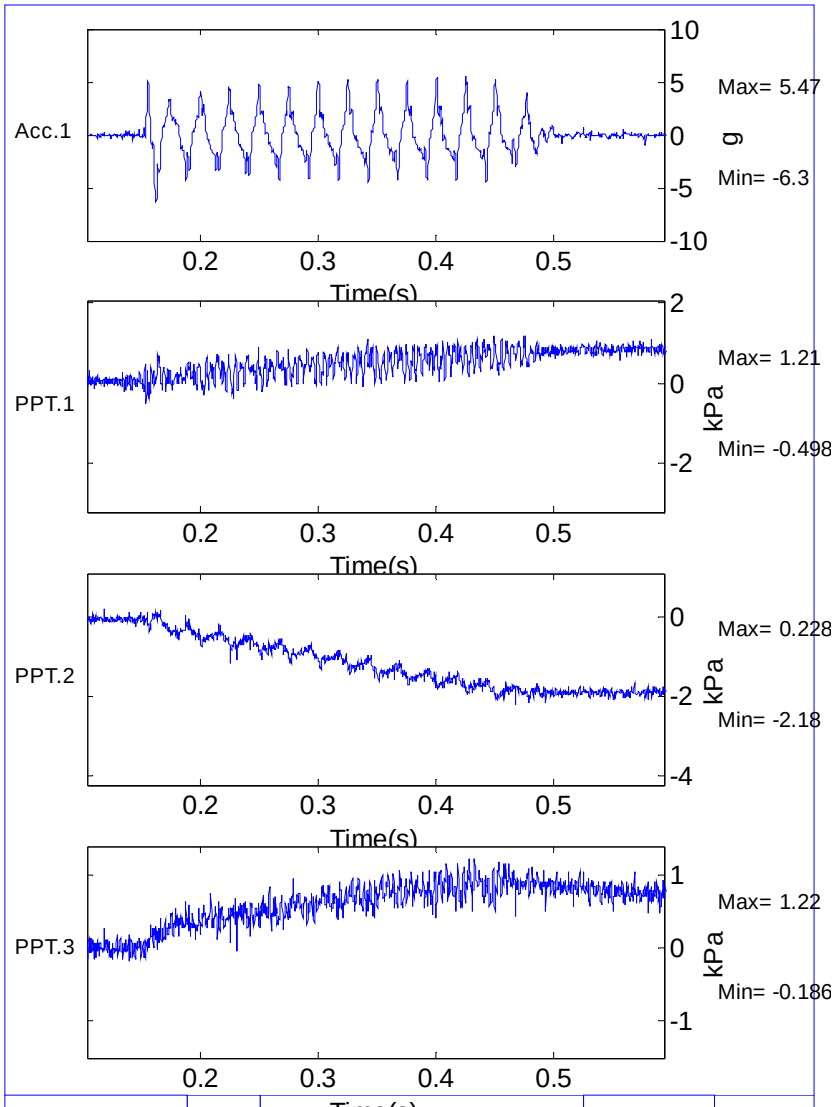


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

6. Data from Test IT04, Earthquake 2.

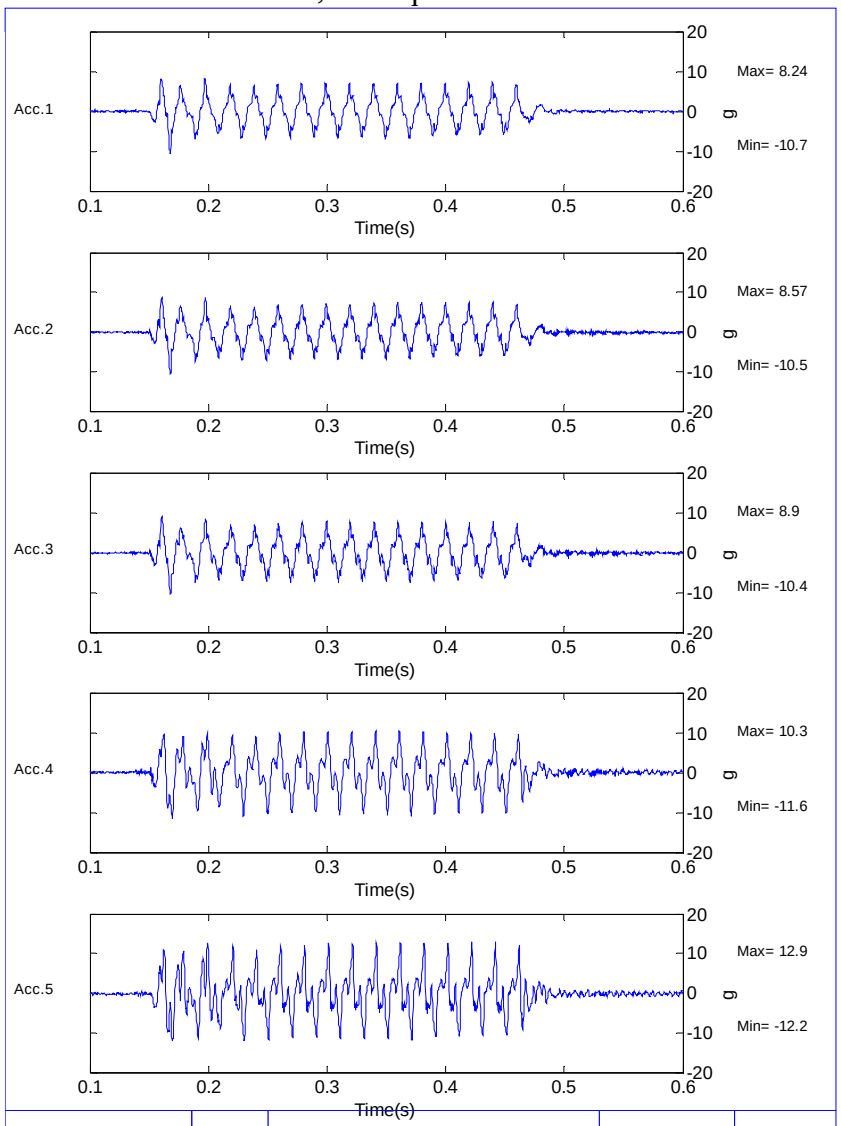


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

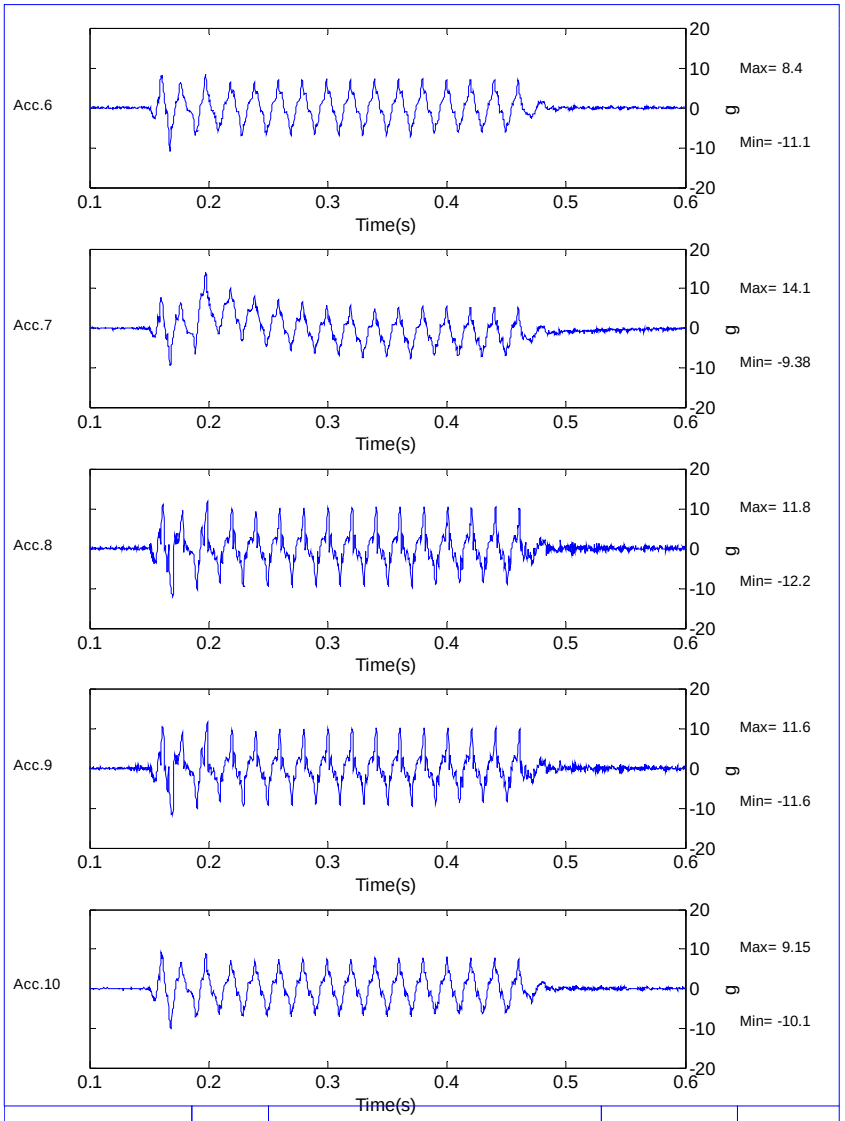


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No
FLIGHT 1		Short-Term Time Records	2	

7. Data from Test IT04, Earthquake 3.

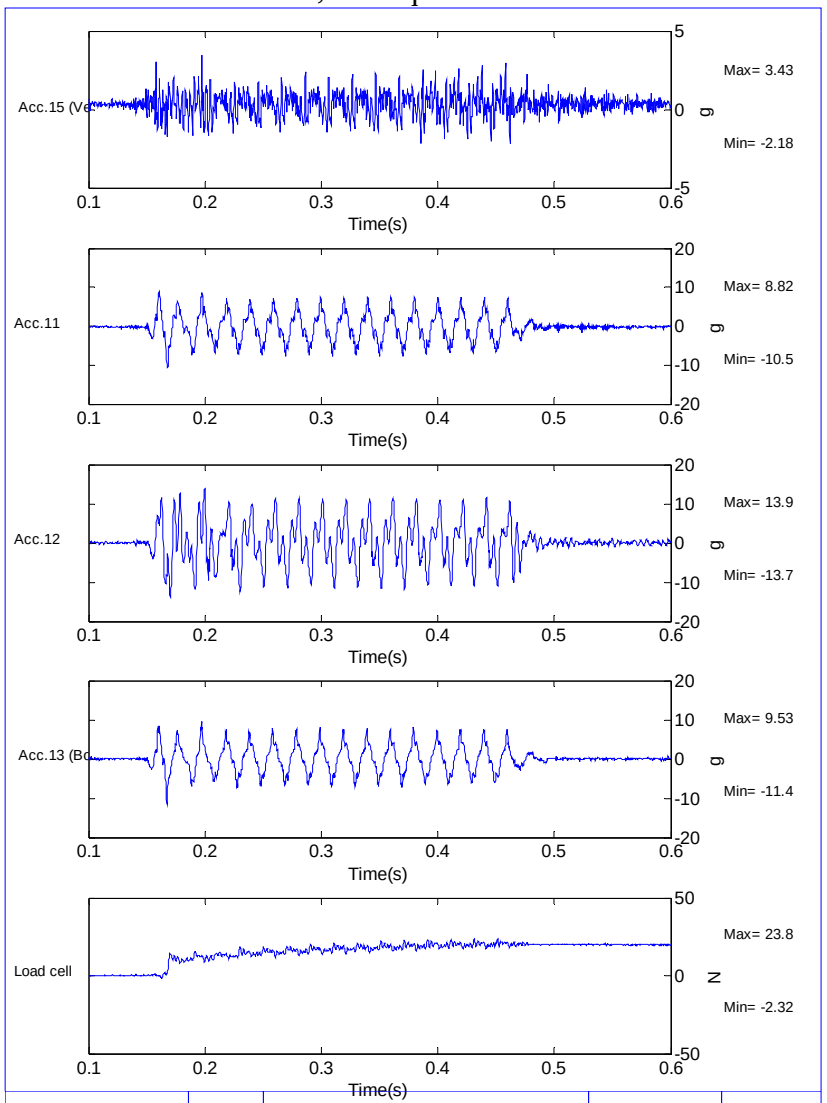


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

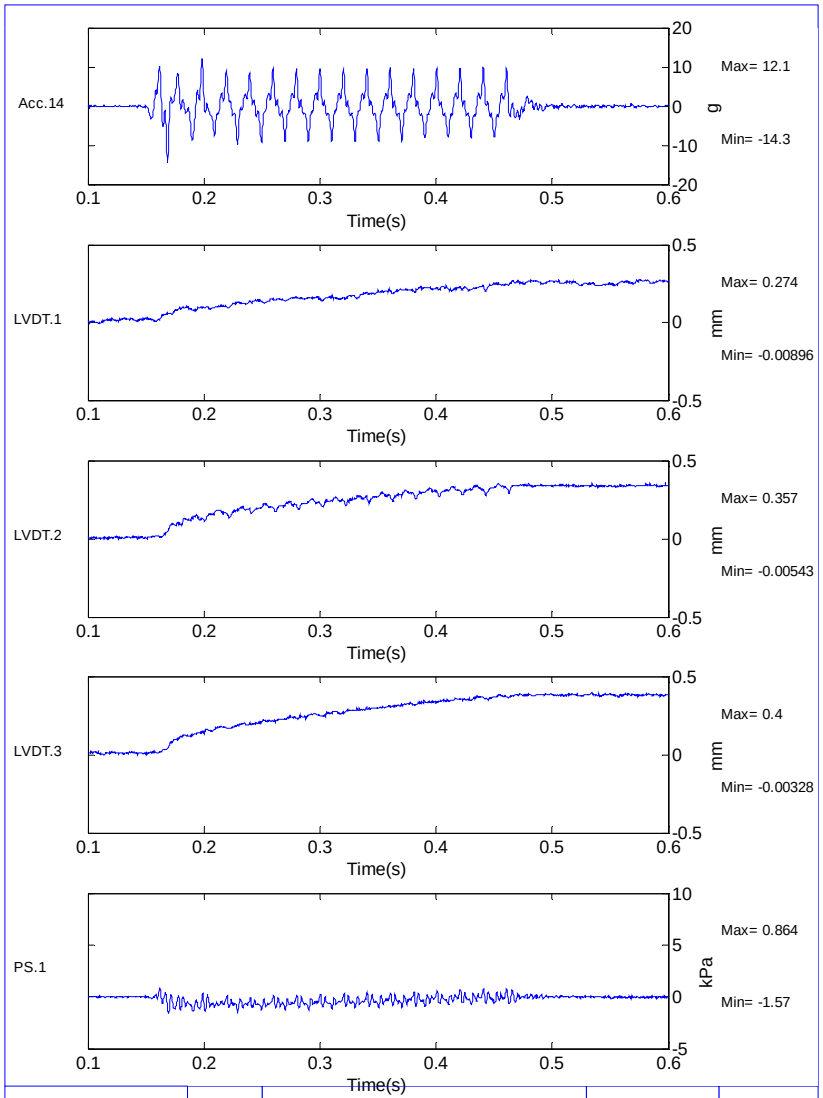


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

8. Data from Test IT04, Earthquake 3.

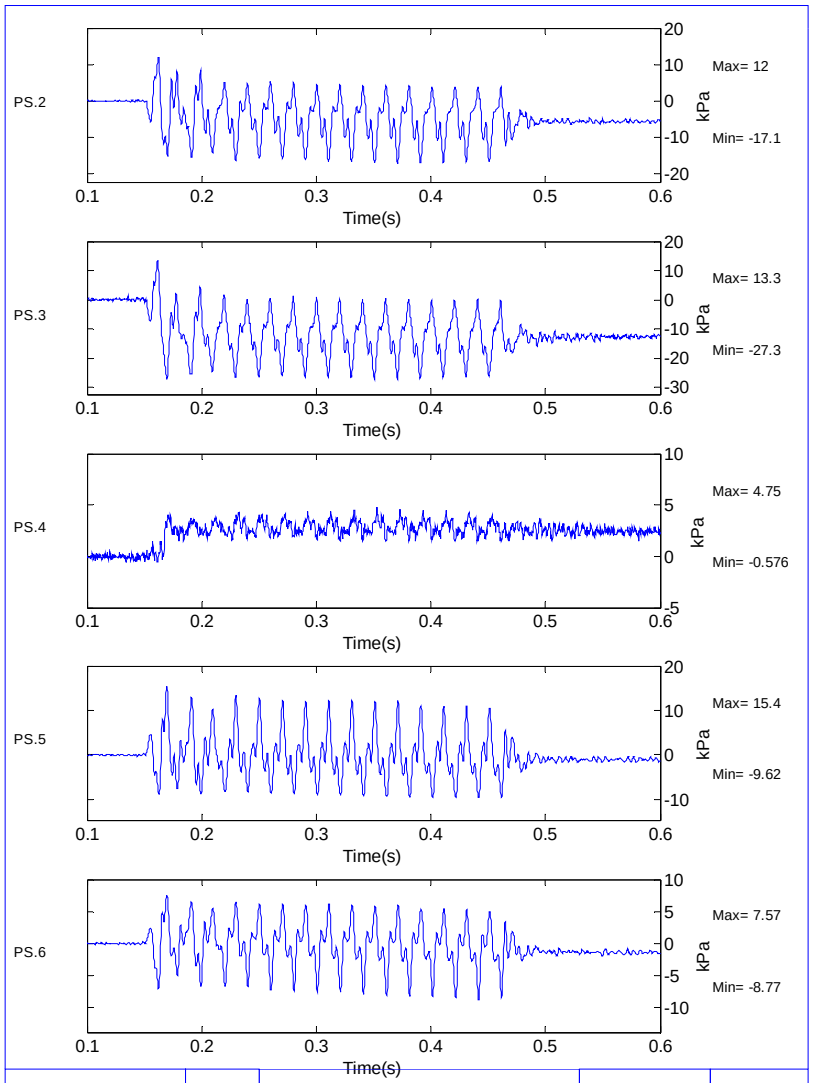


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

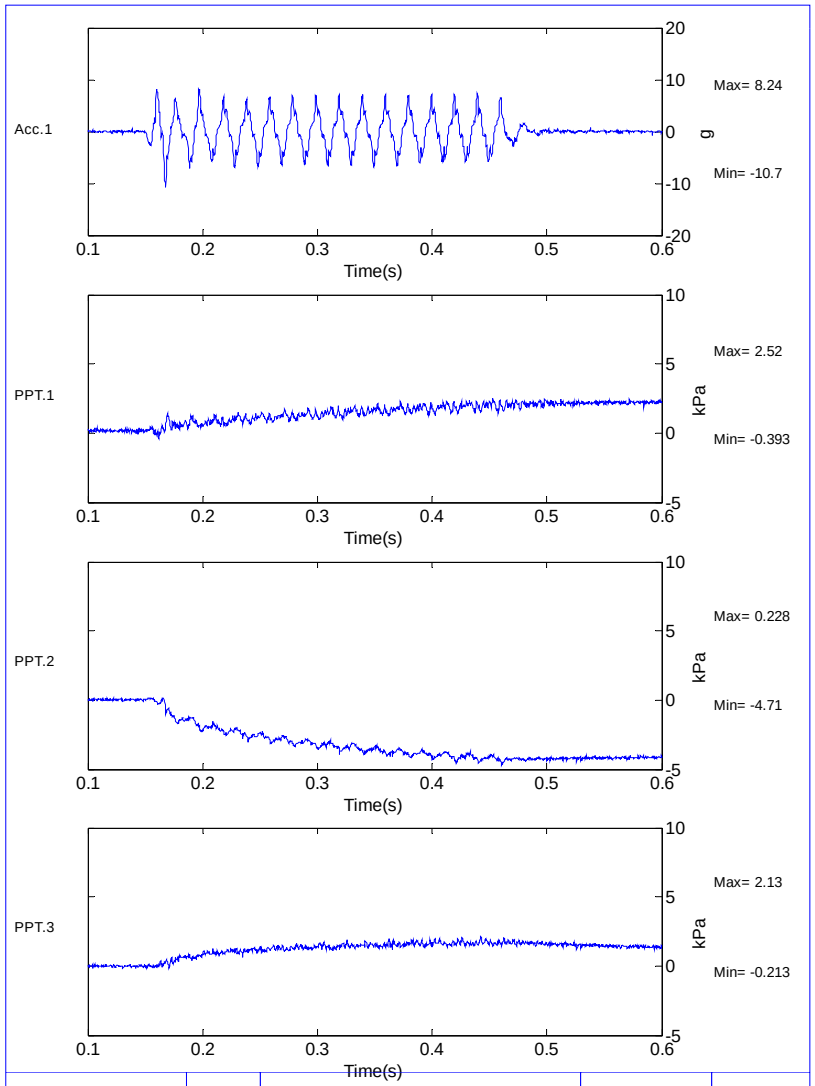


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

9. Data from Test IT04, Earthquake 3.

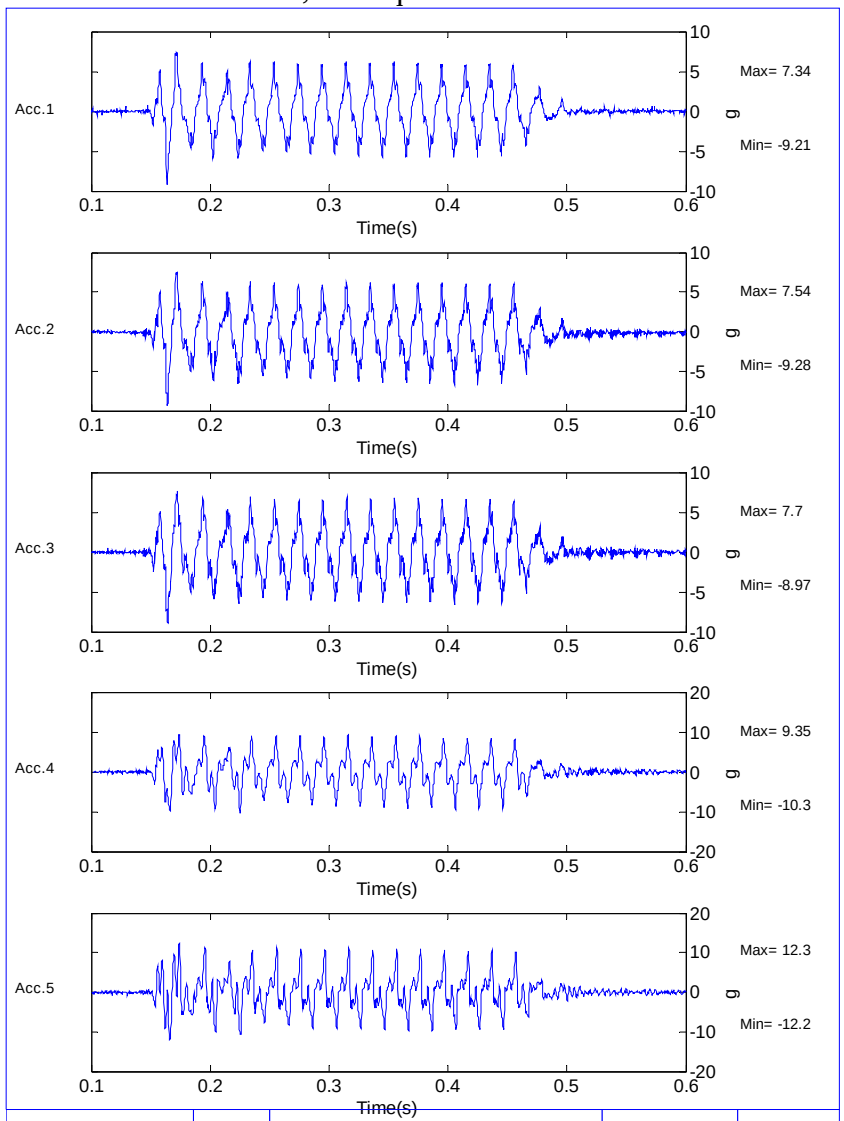


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

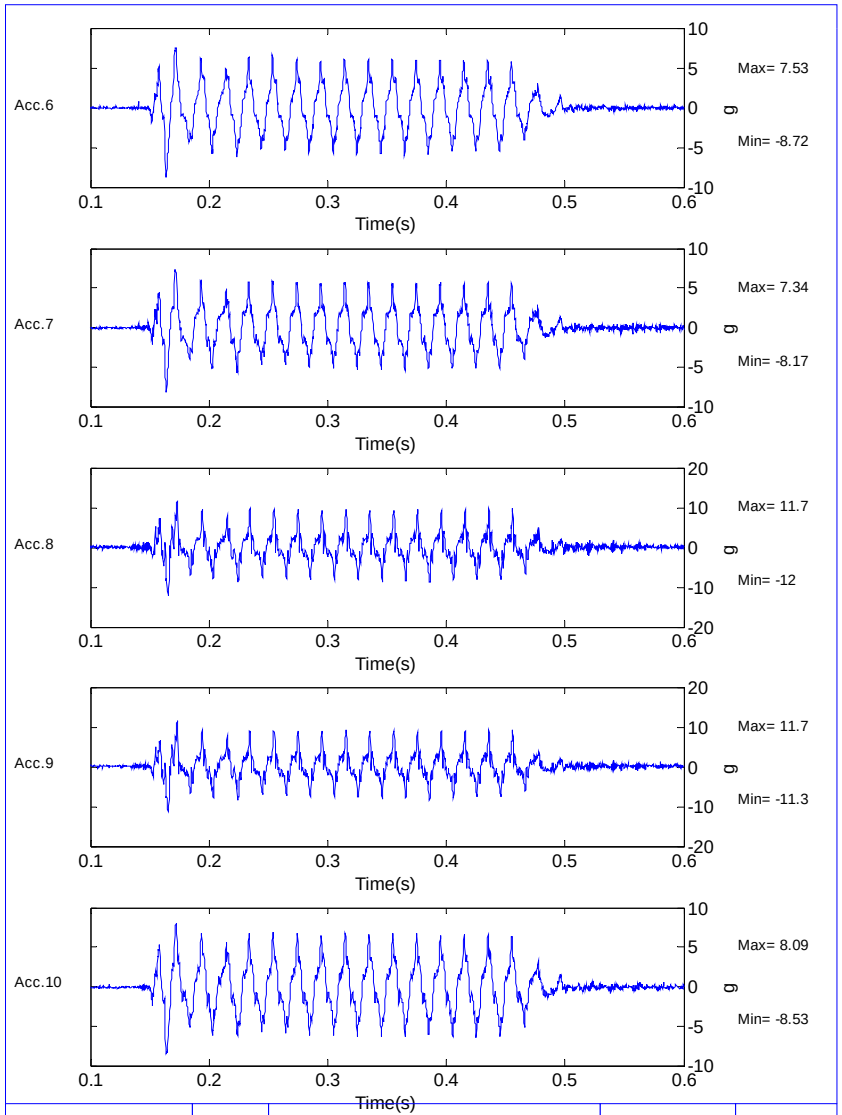


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

10. Data from Test IT04, Earthquake 4.

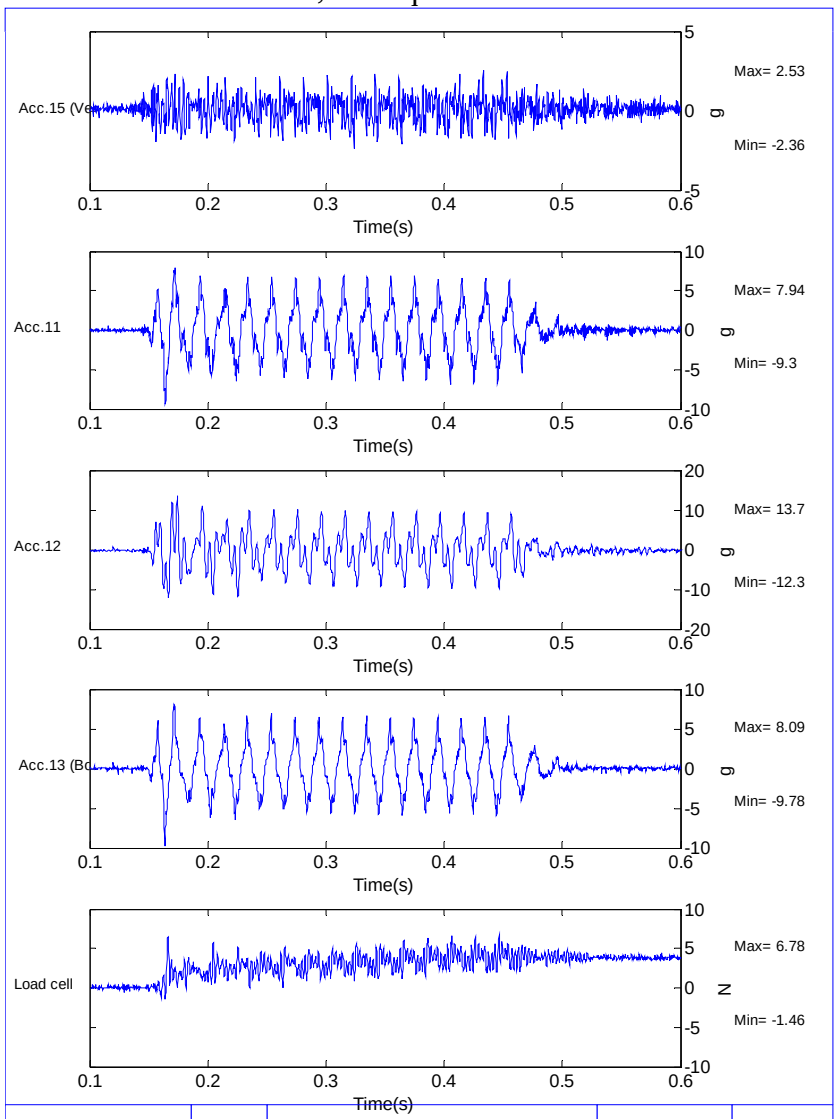


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 4	Figure No.

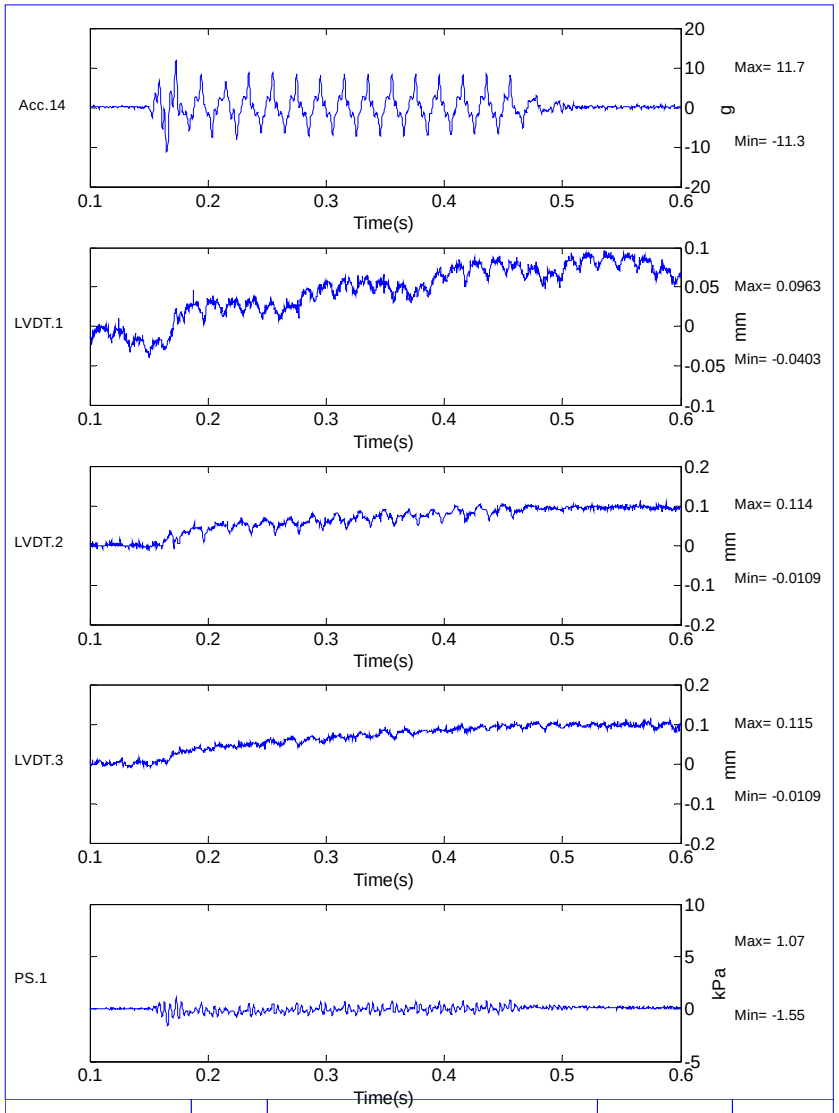


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 4	Figure No.

11. Data from Test IT04, Earthquake 4.

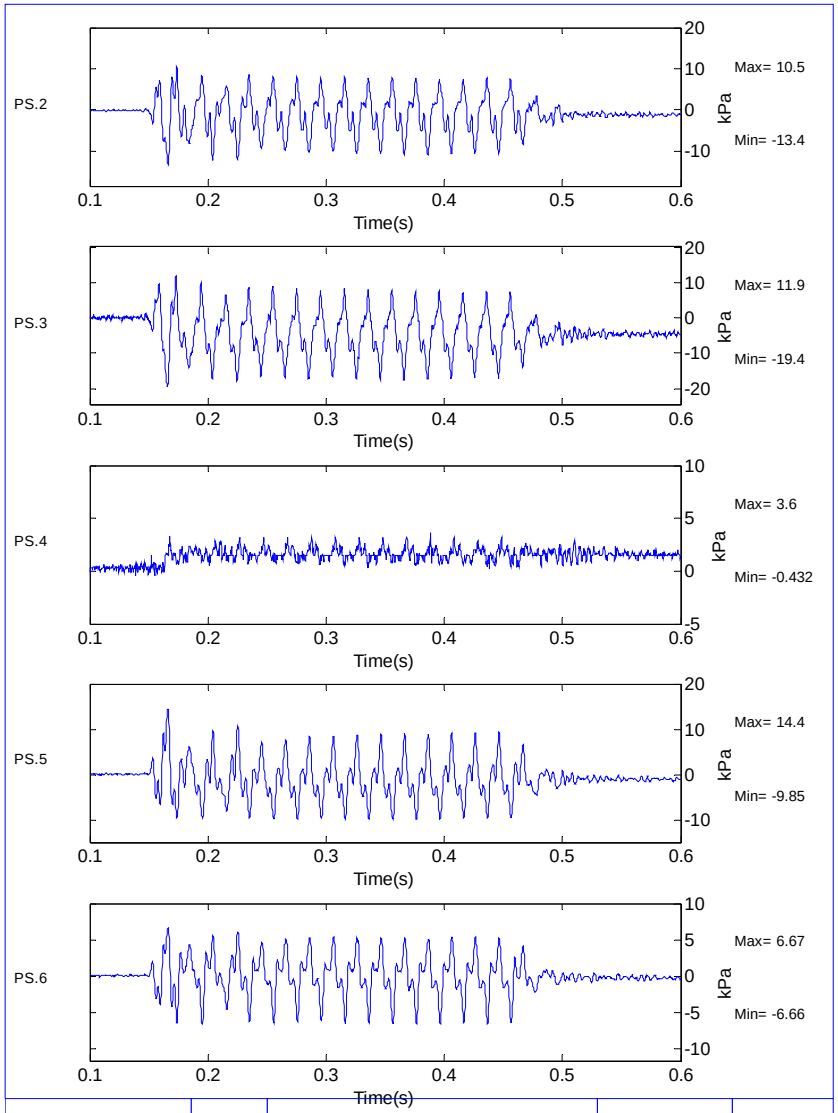


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

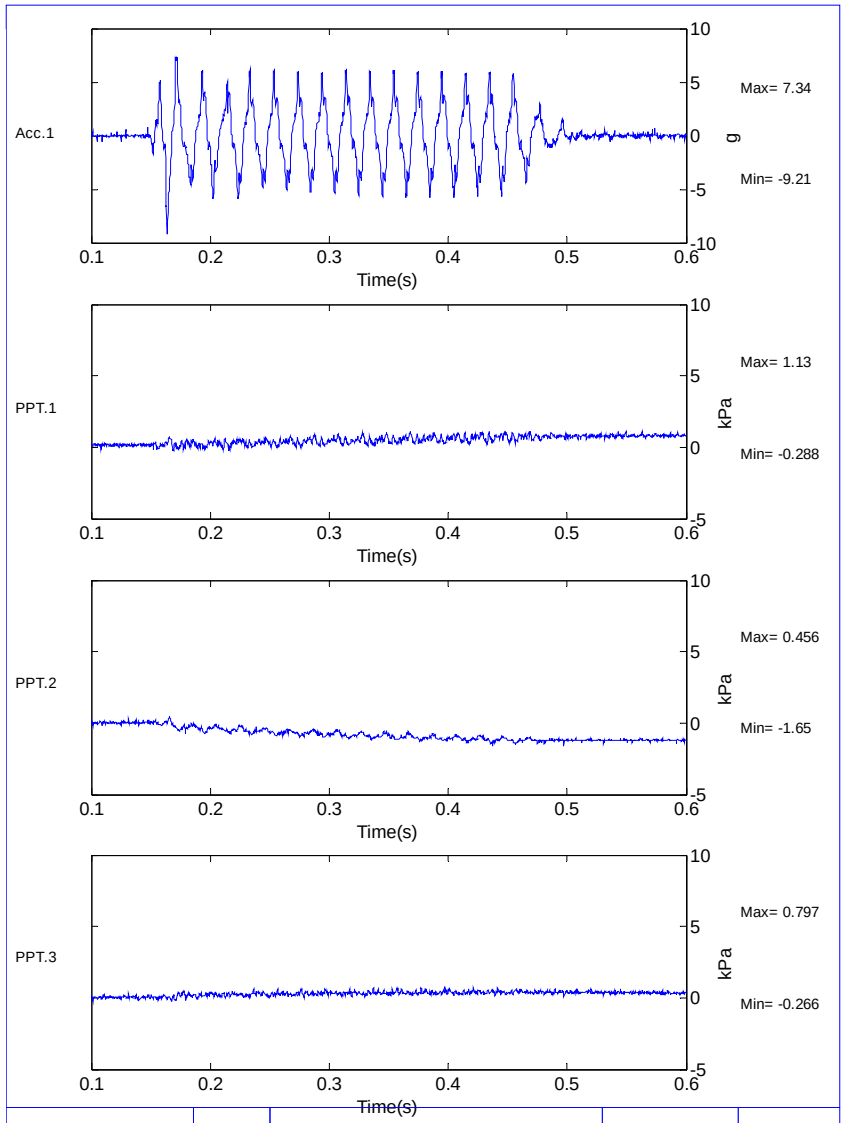


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

12. Data from Test IT04, Earthquake 4.

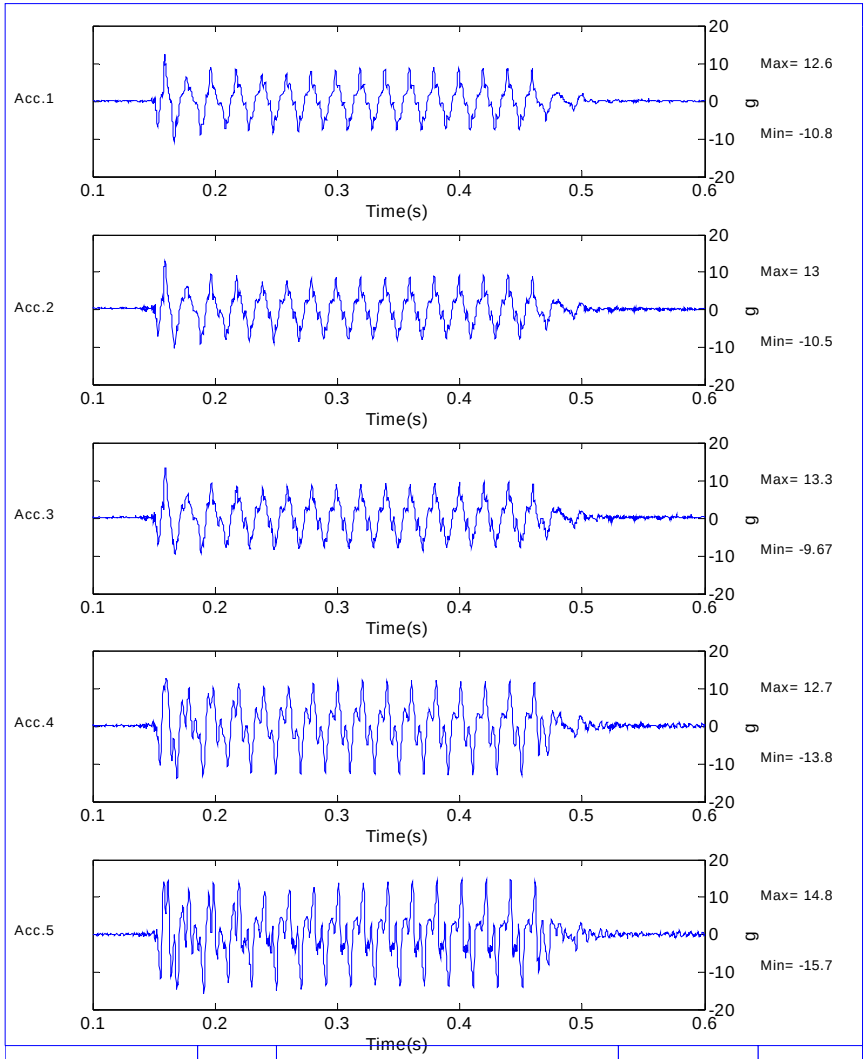


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

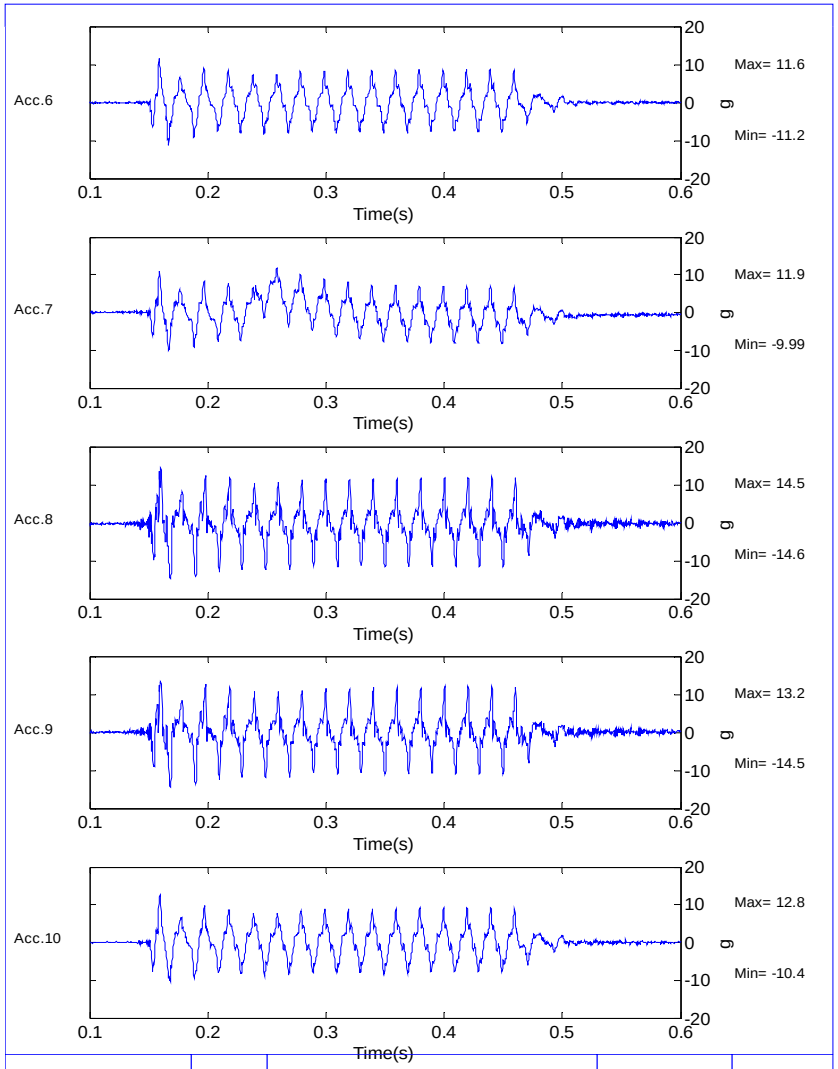


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

13. Data from Test IT04, Earthquake 5.

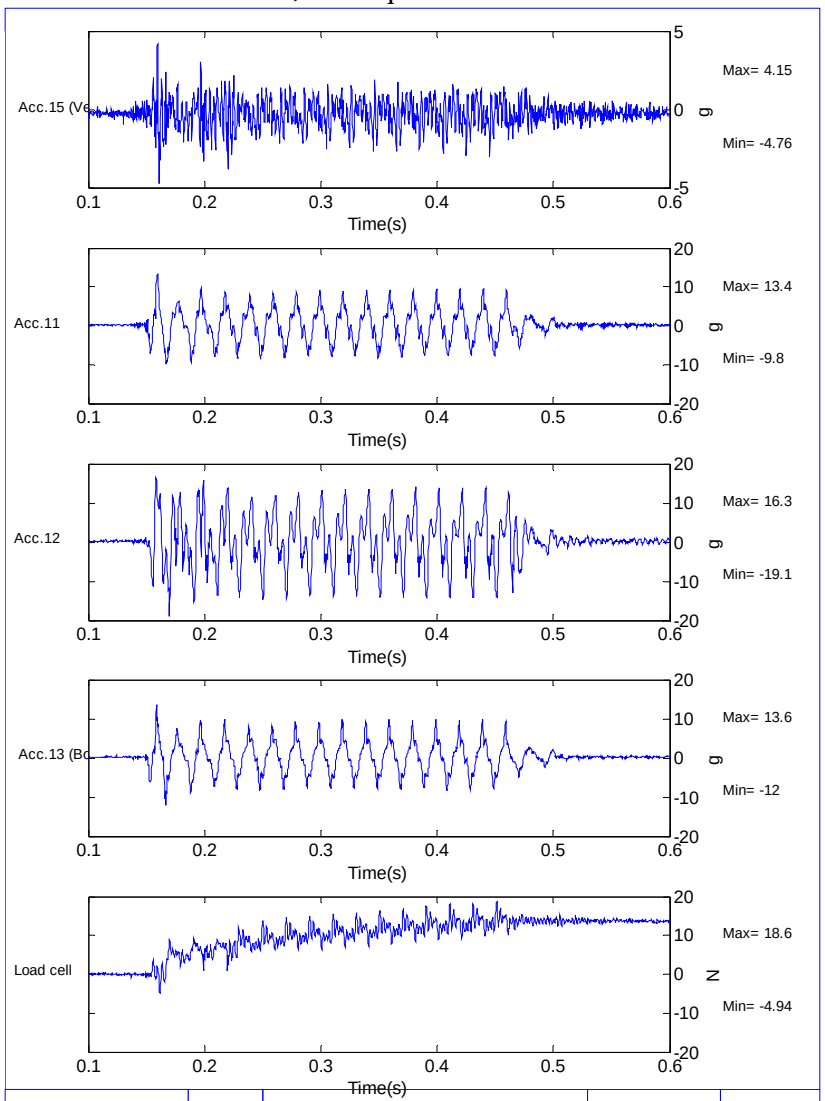


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

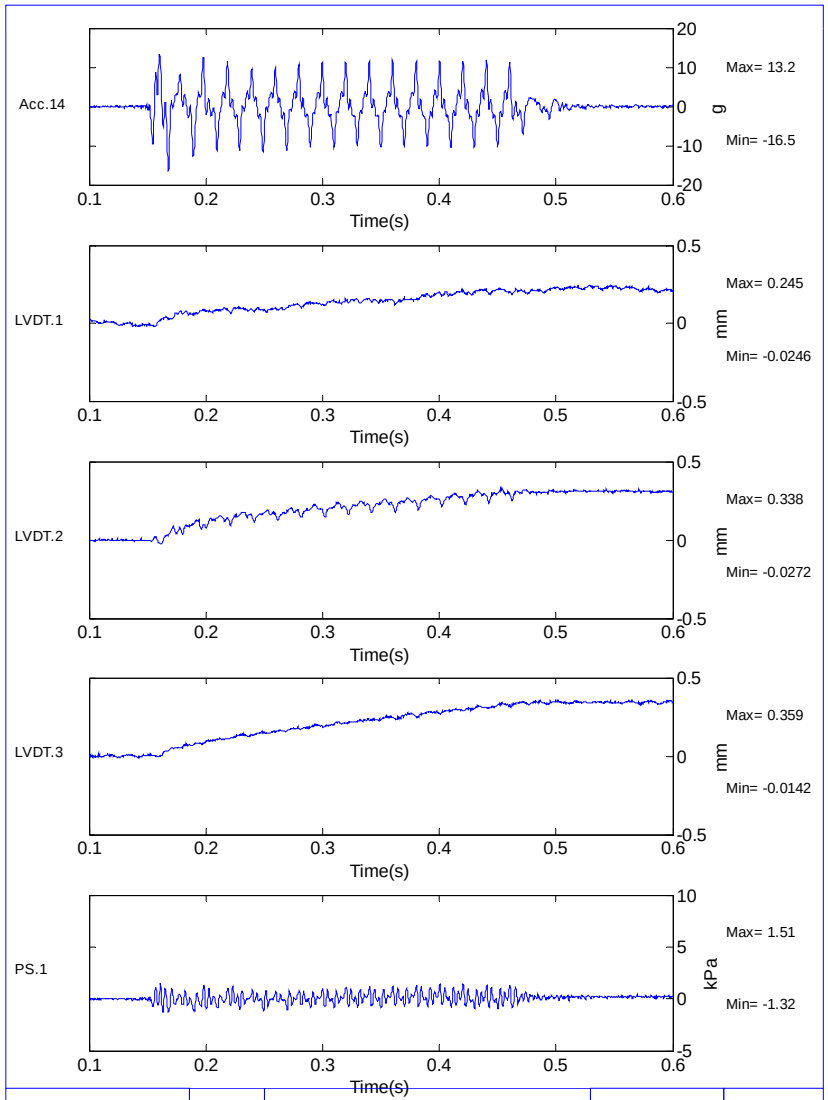


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

14. Data from Test IT04, Earthquake 5.

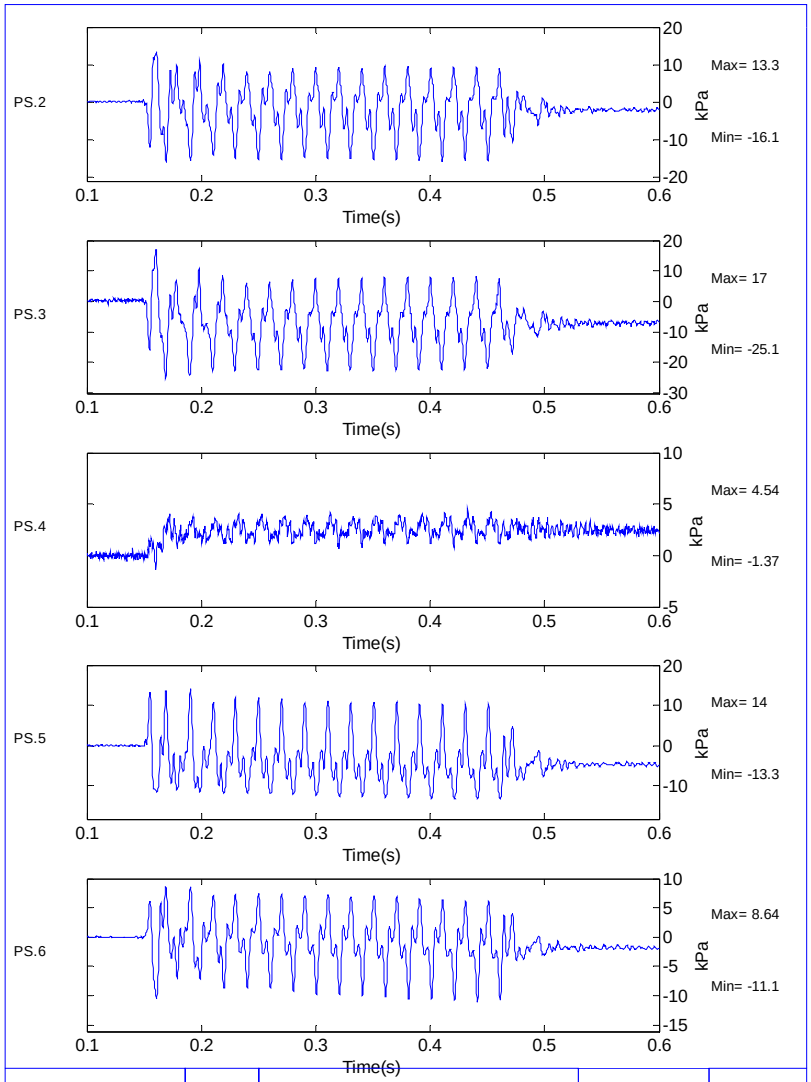


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

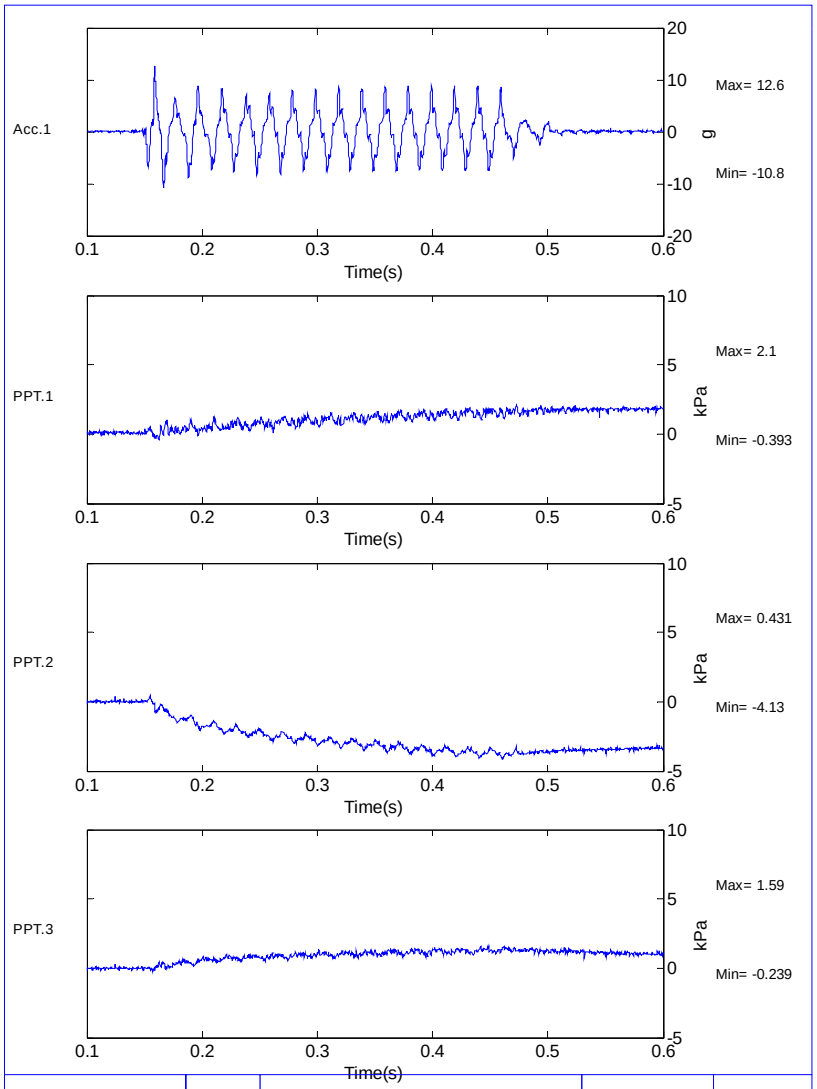


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

15. Data from Test IT04, Earthquake 5.

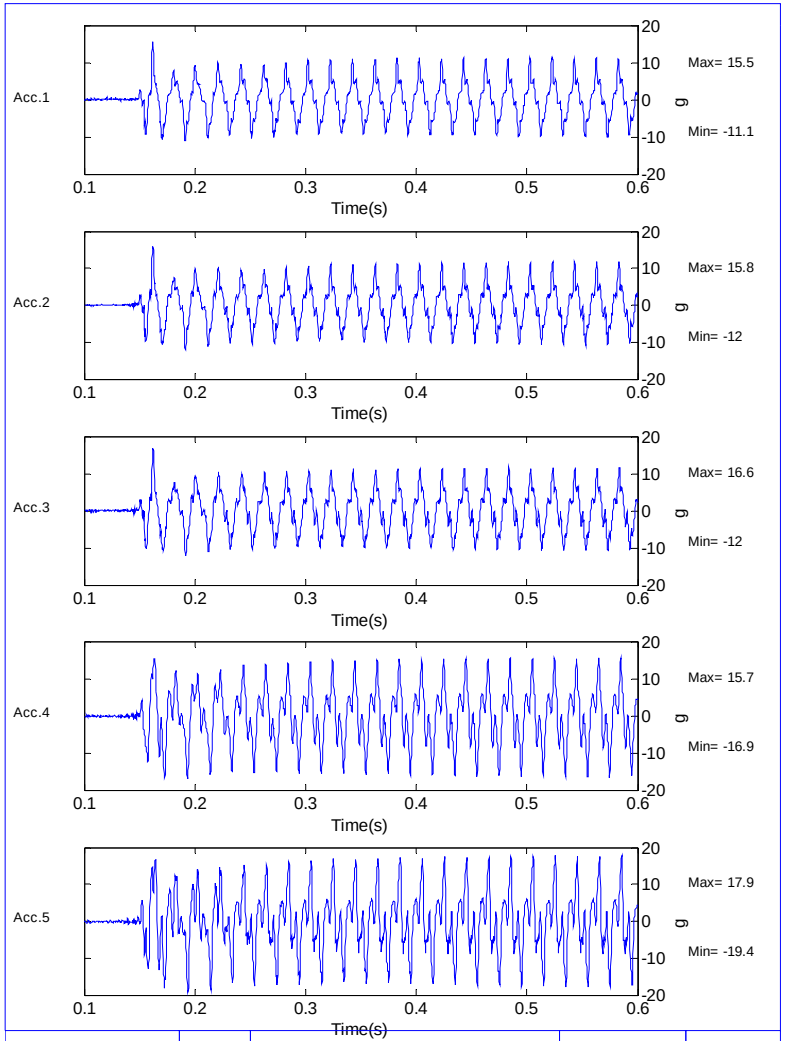


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

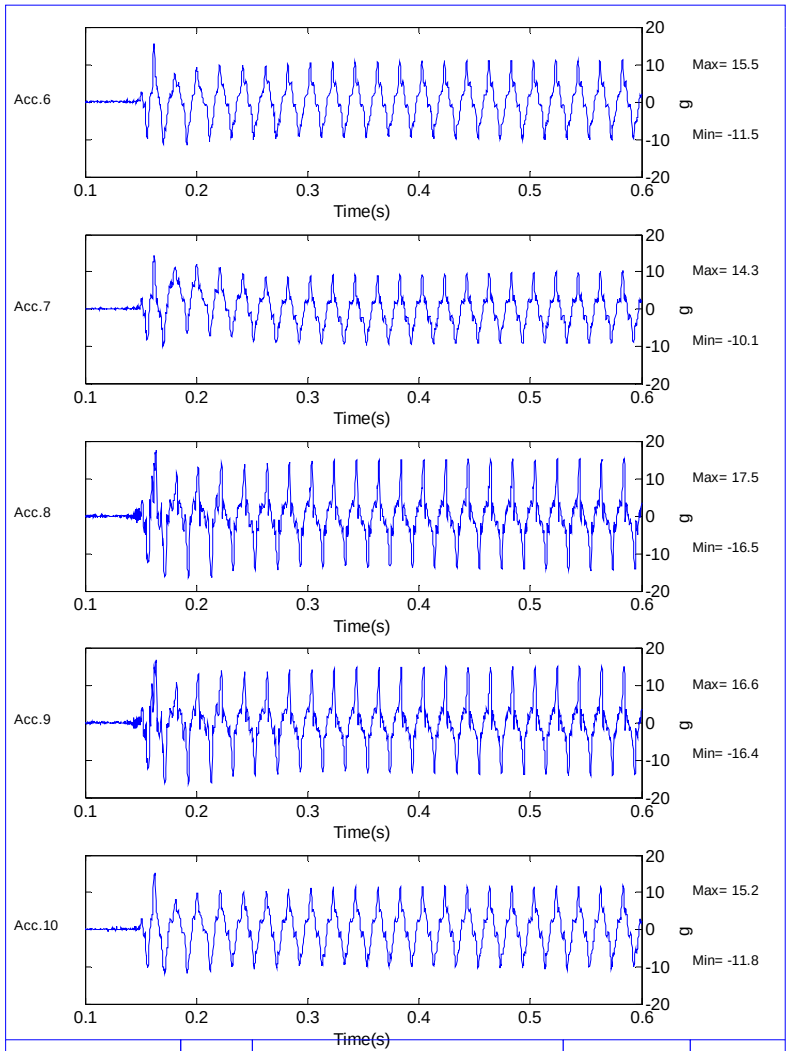


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

16. Data from Test IT04, Earthquake 6.

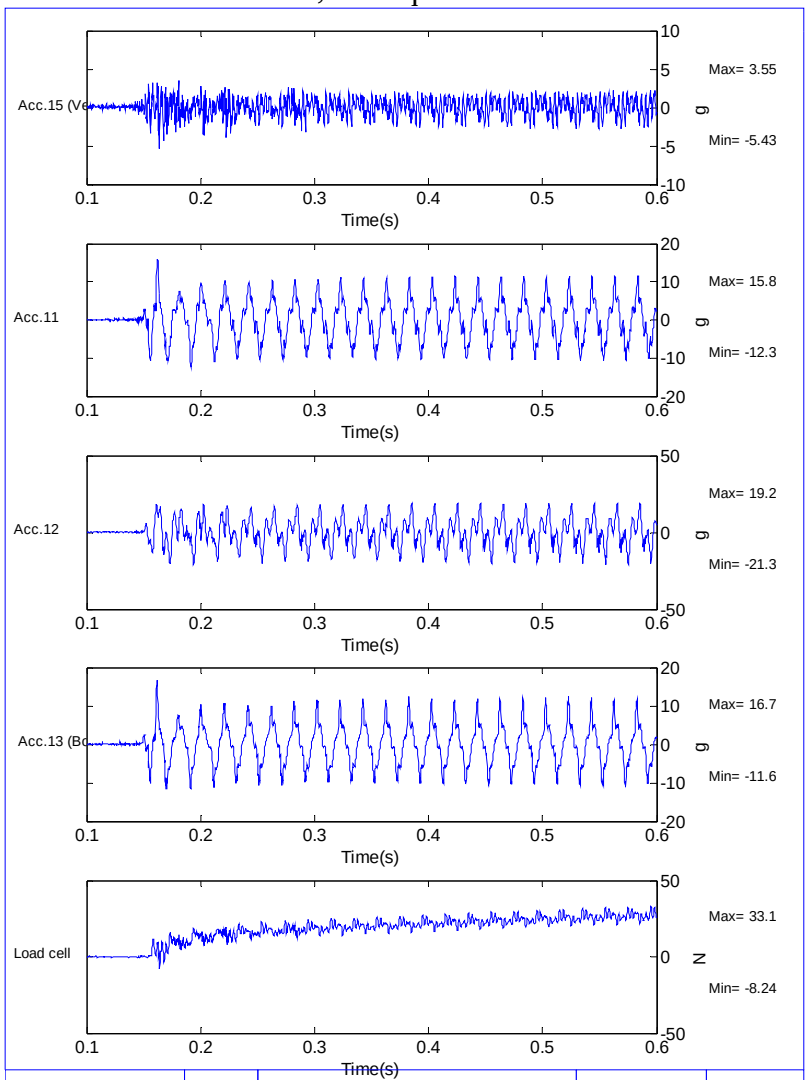


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 6	Figure No.

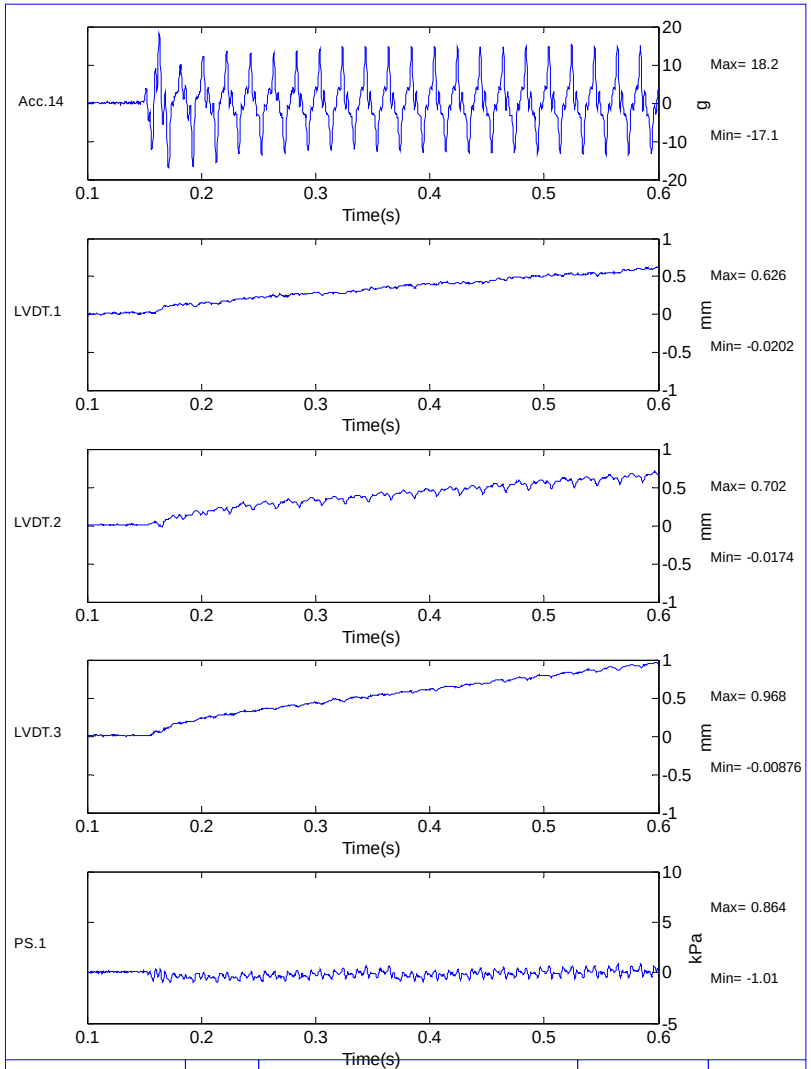


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 6	Figure No.

17. Data from Test IT04, Earthquake 6.

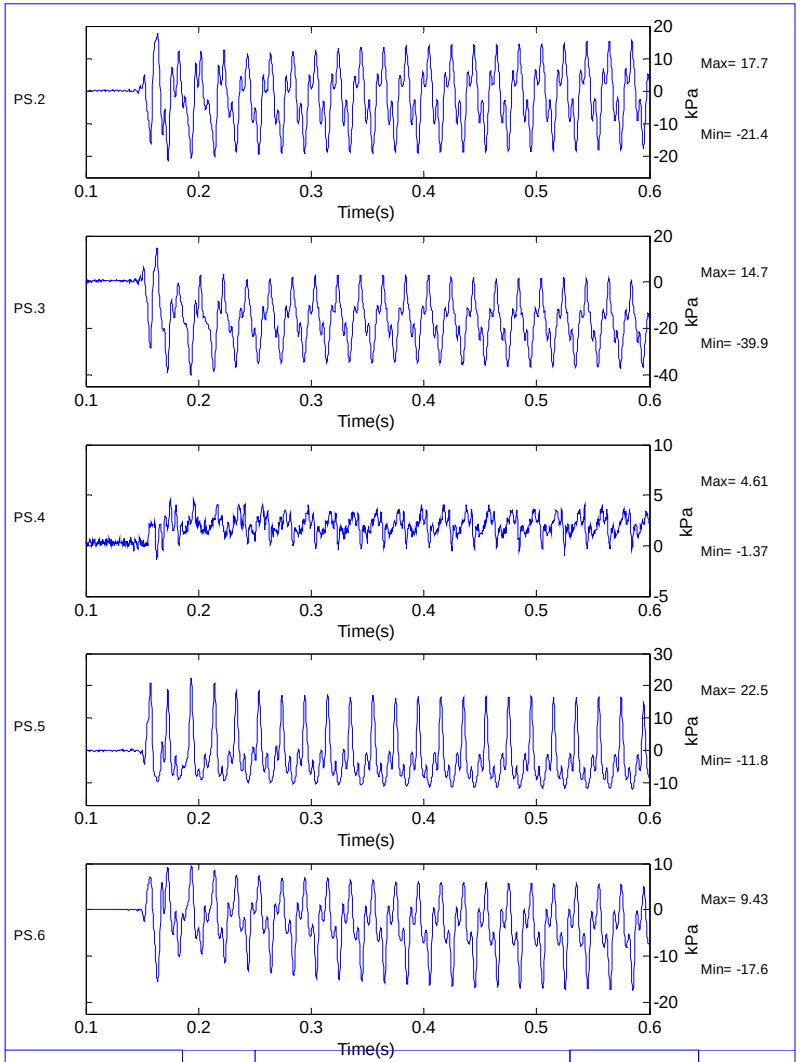


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 6	Figure No.

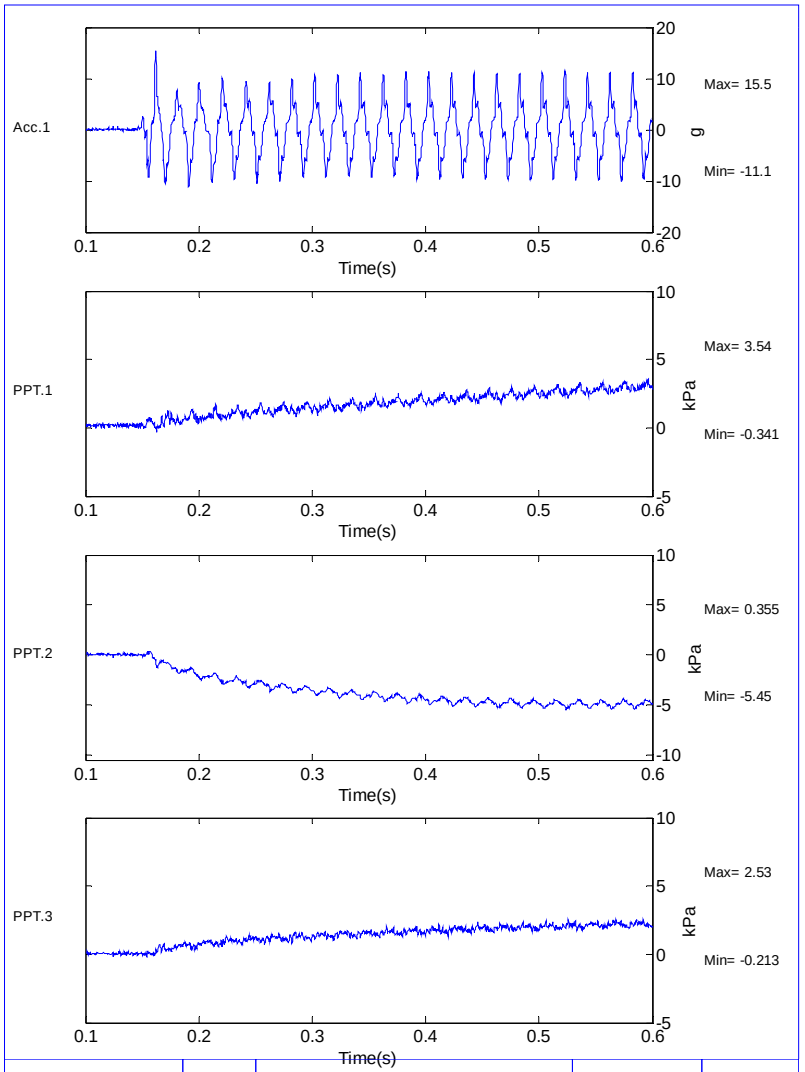


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 6	Figure No.

18. Data from Test IT04, Earthquake 6.

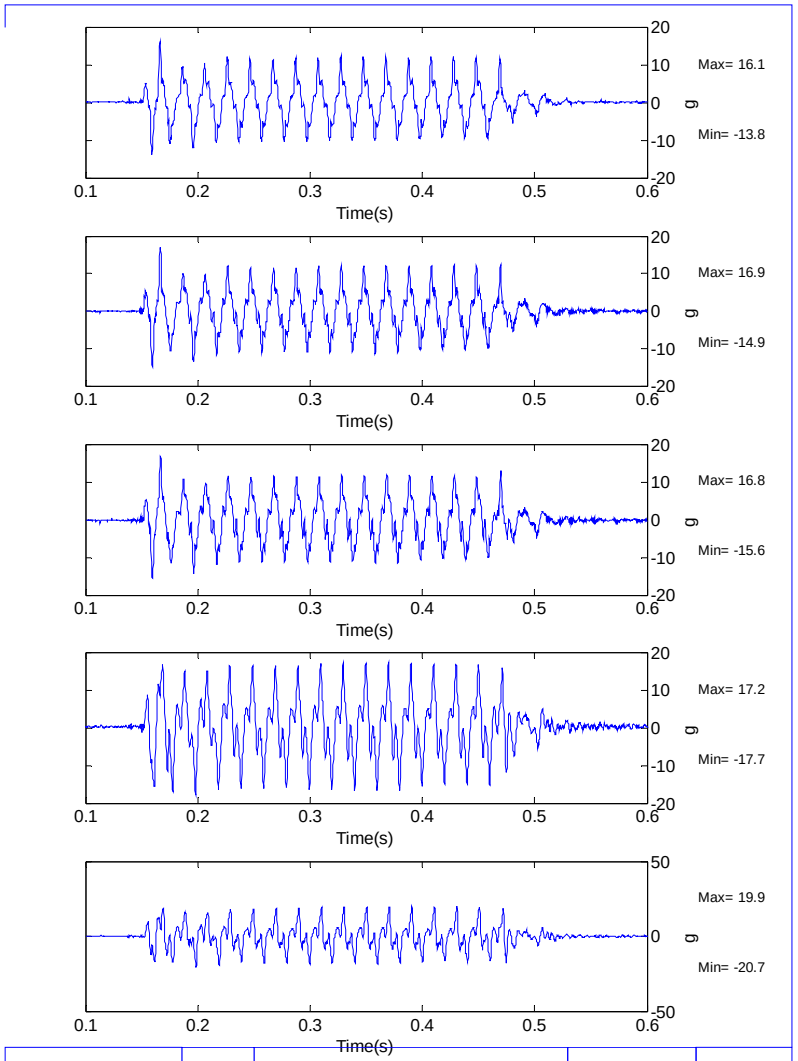


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	

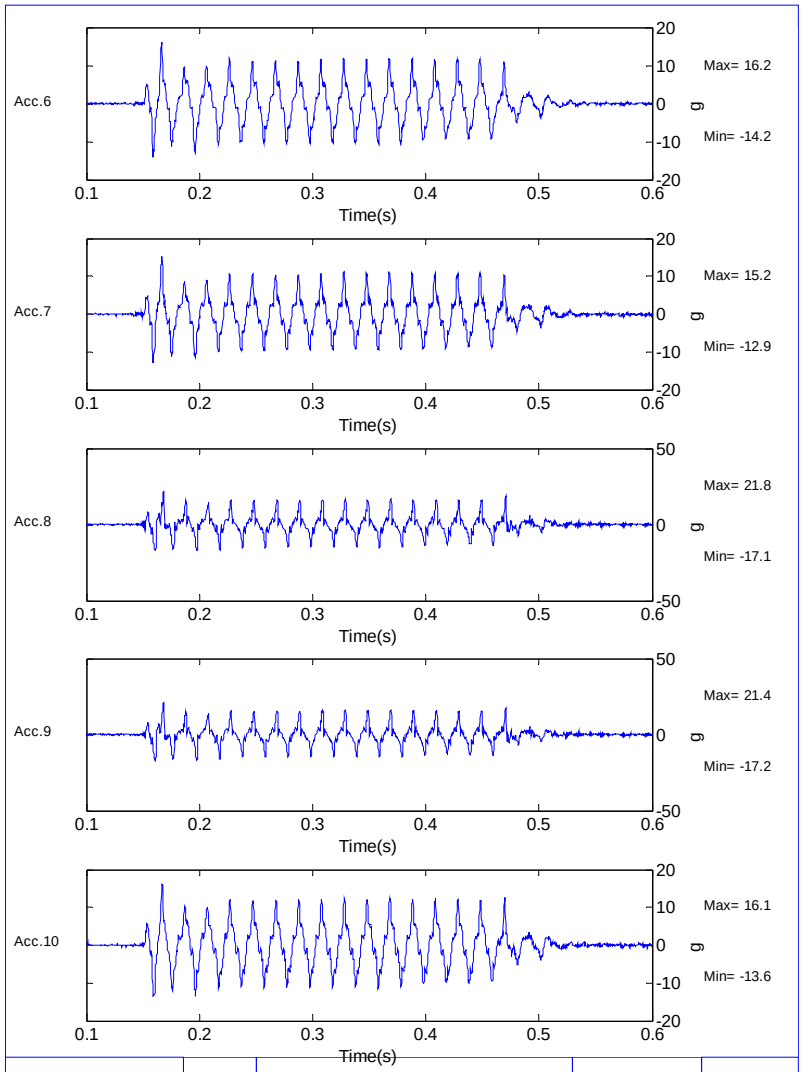


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	

19. Data from Test IT04, Earthquake 7.

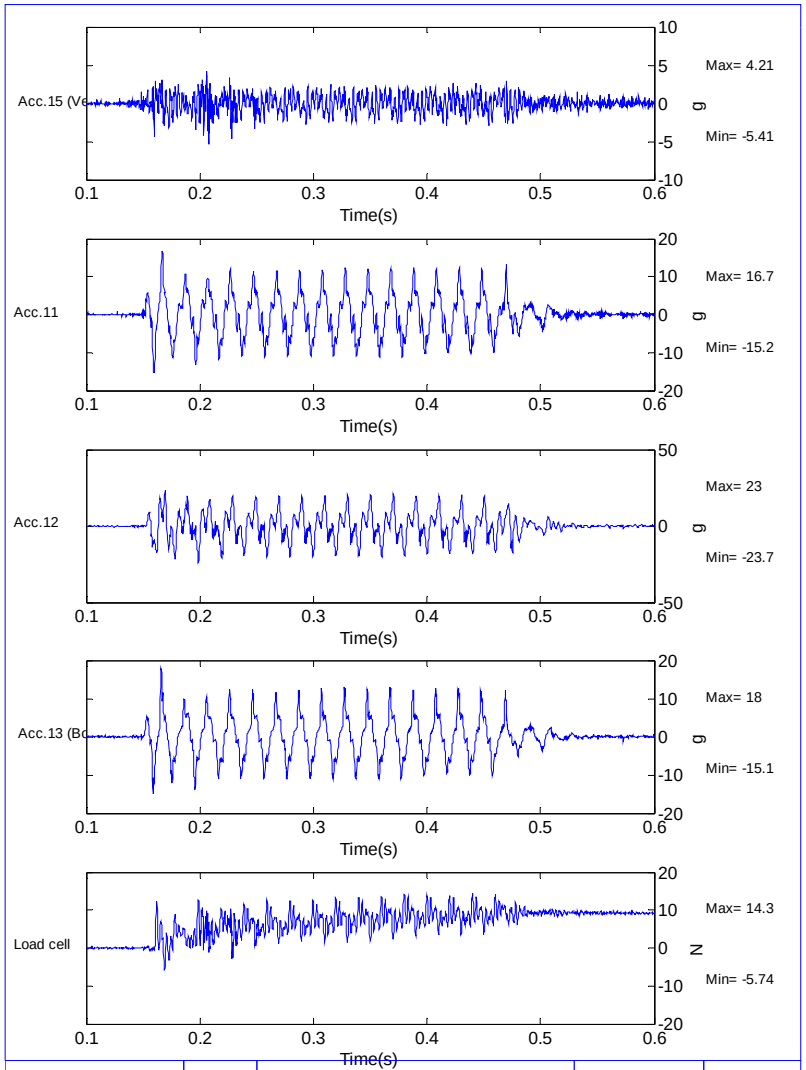


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 7	Figure No.

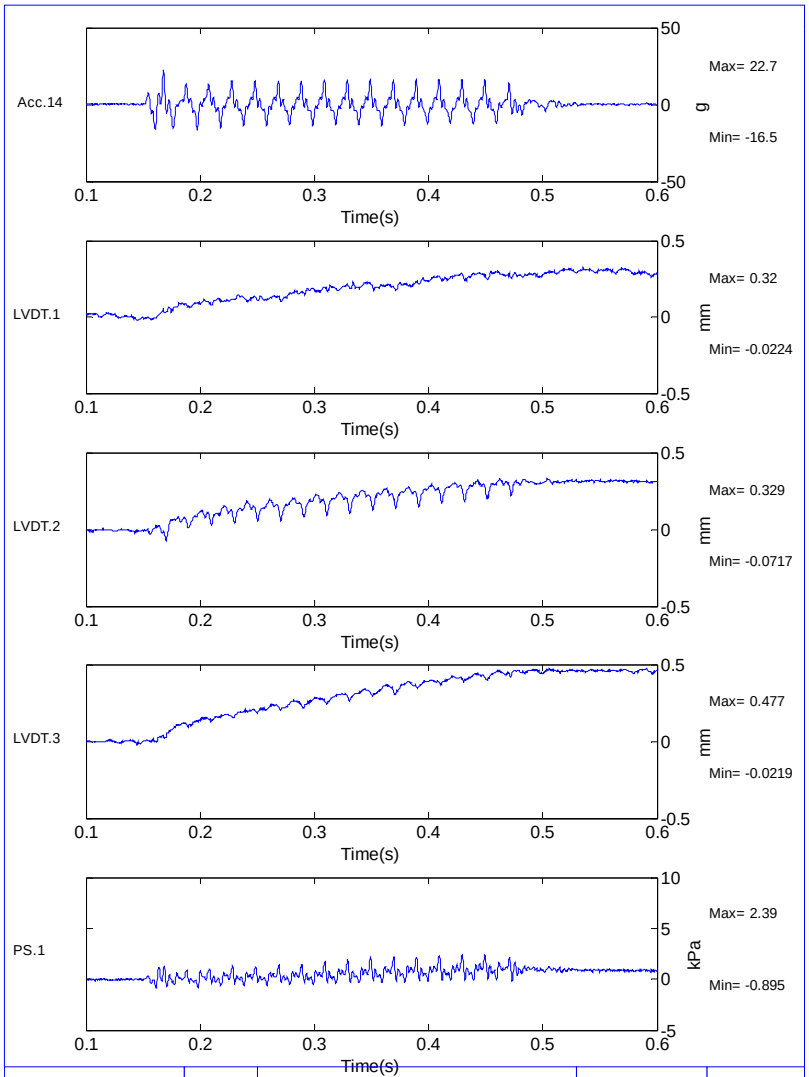


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 7	Figure No.

20. Data from Test IT04, Earthquake 7.

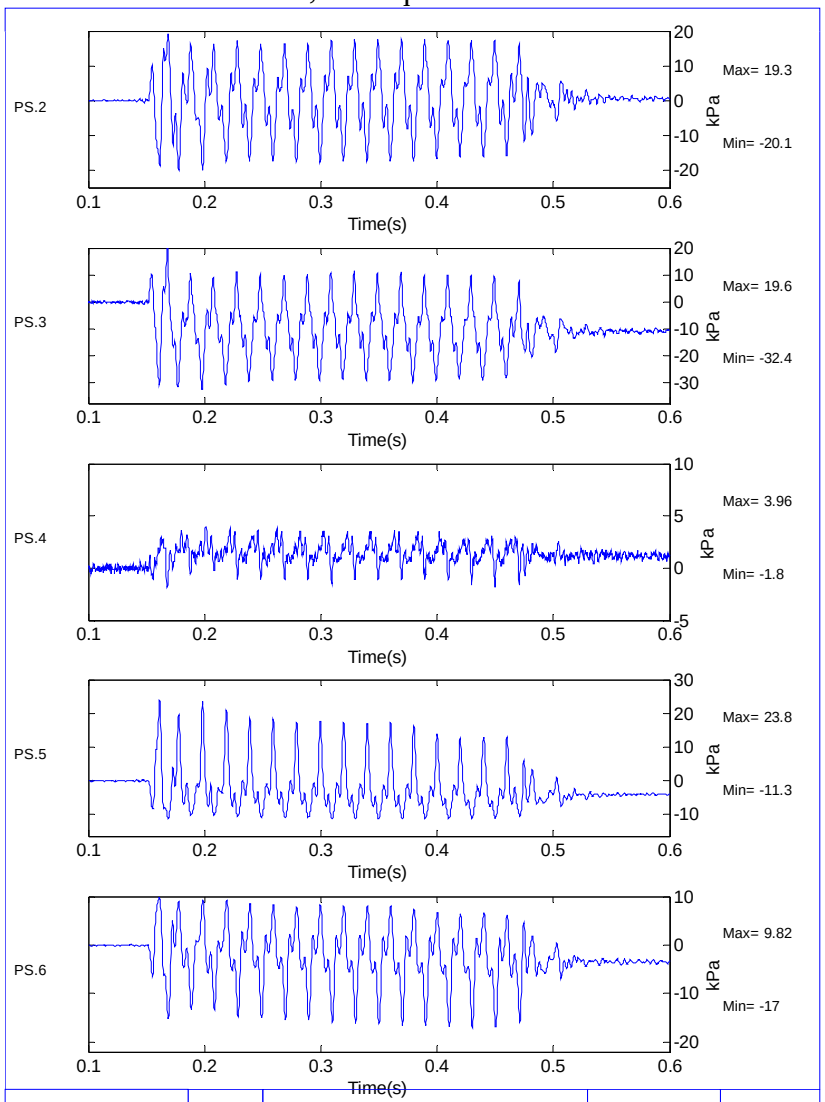


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 7	Figure No.

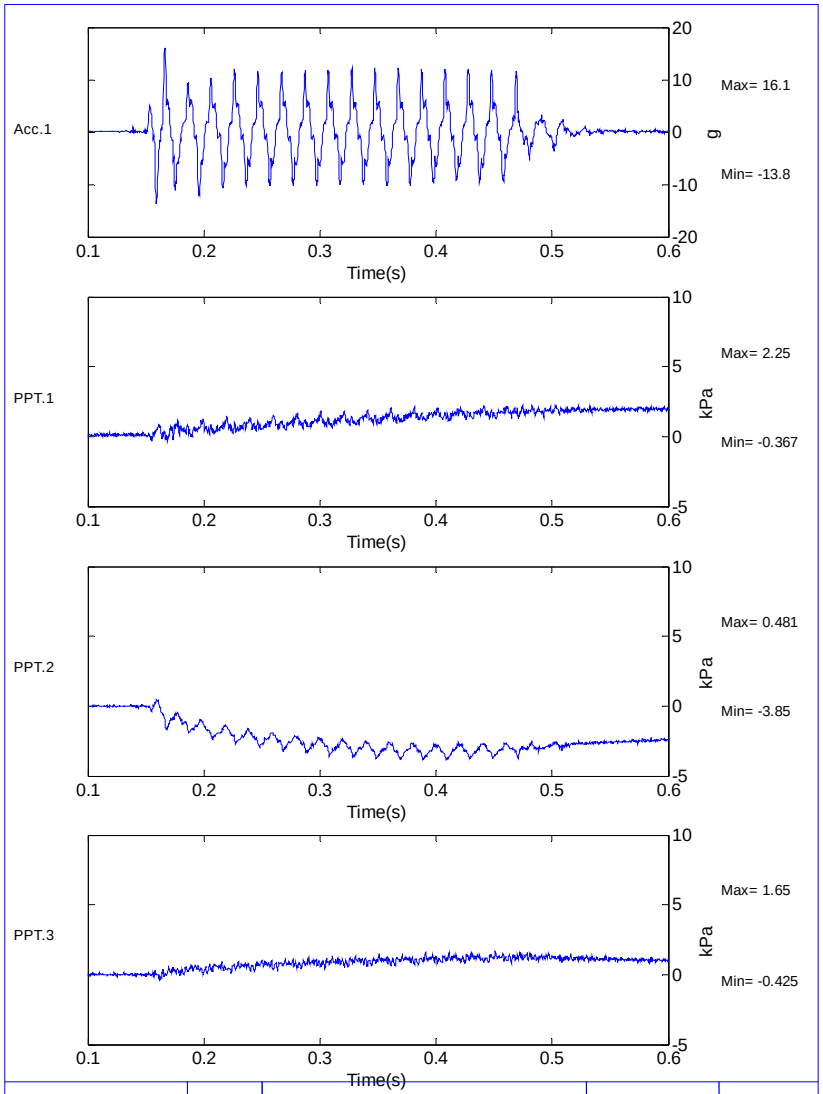


TEST IT04 FLIGHT 1		Scales: Model Unfiltered Data Short-Term Time Records	Earthquake 7	Figure No.

21. Data from Test IT04, Earthquake 7.

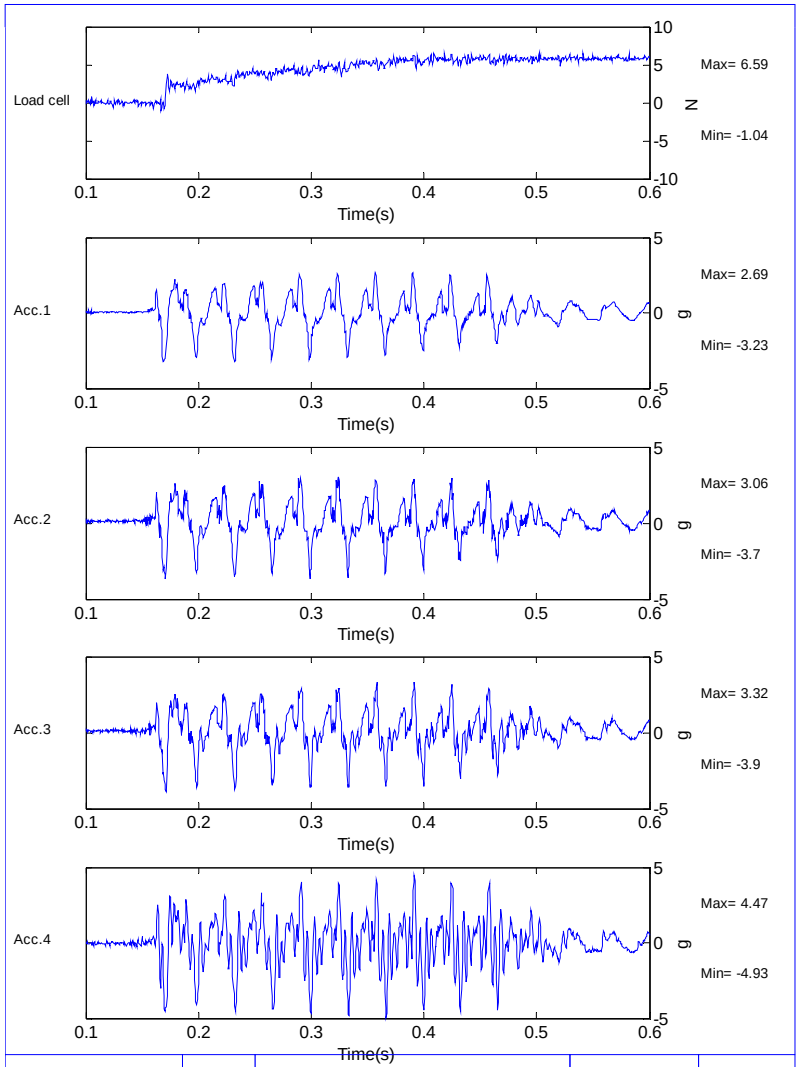


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	7	

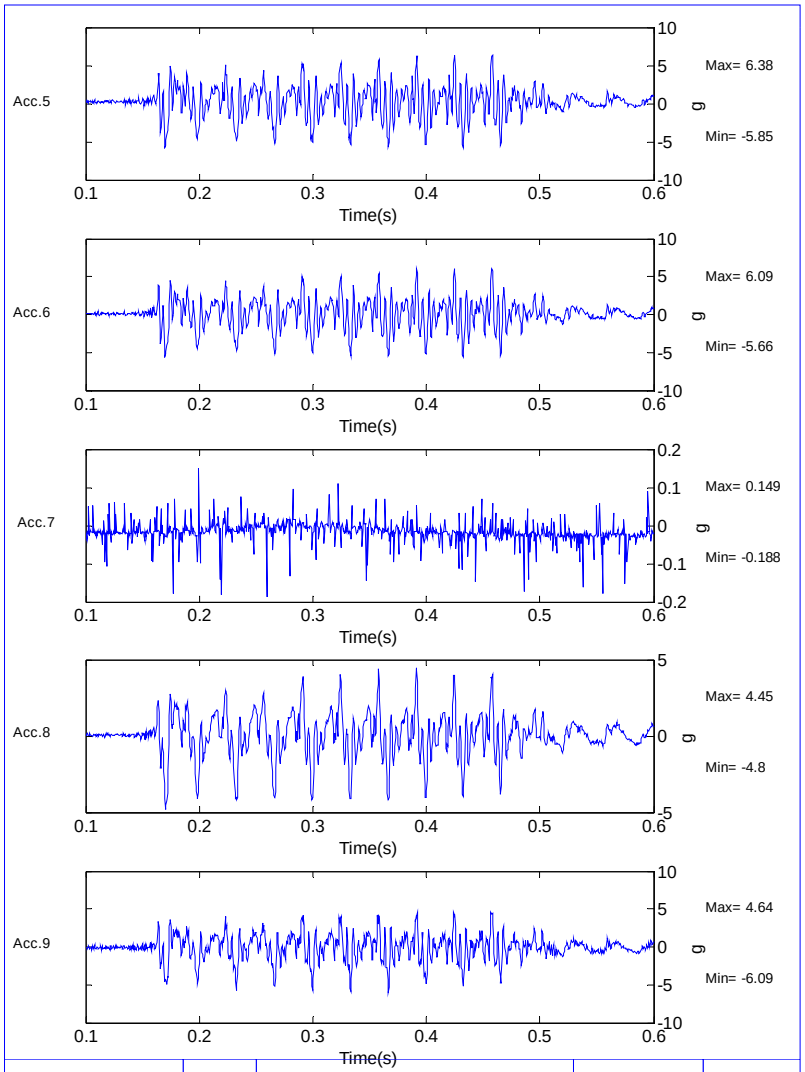


TEST IT04		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	7	

22. Data from Test IT06, Earthquake 1.

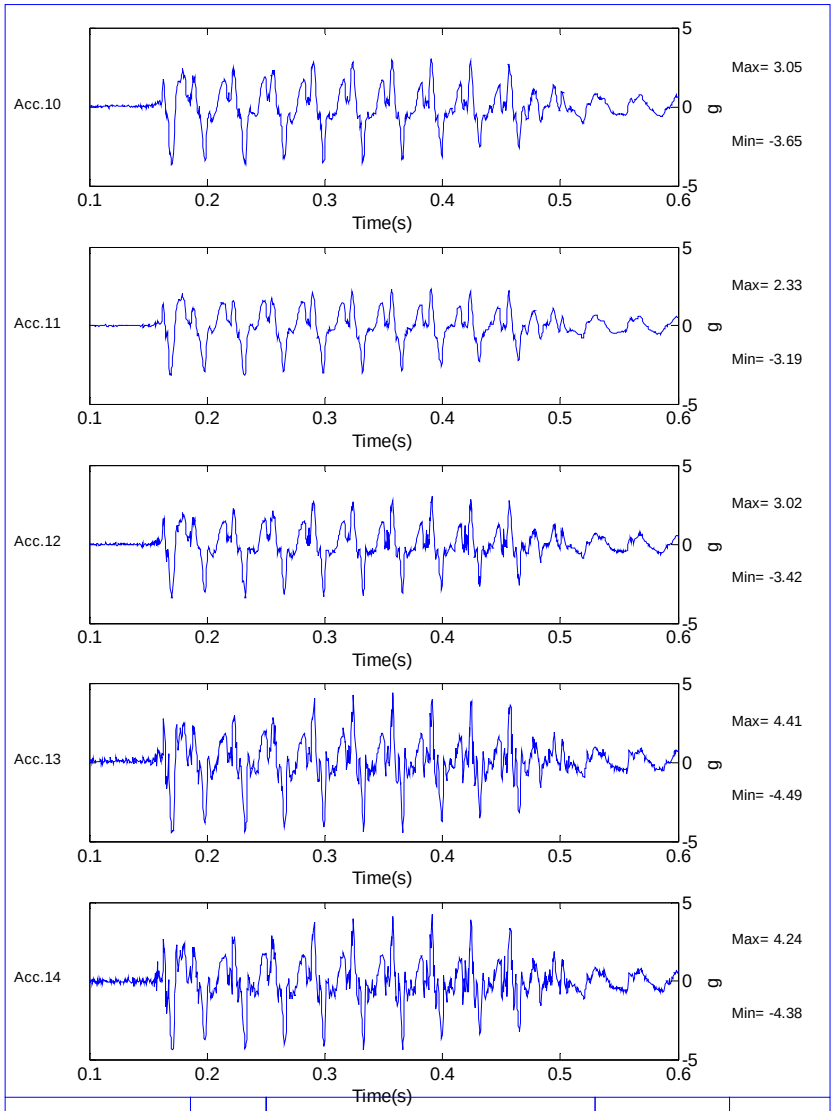


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	

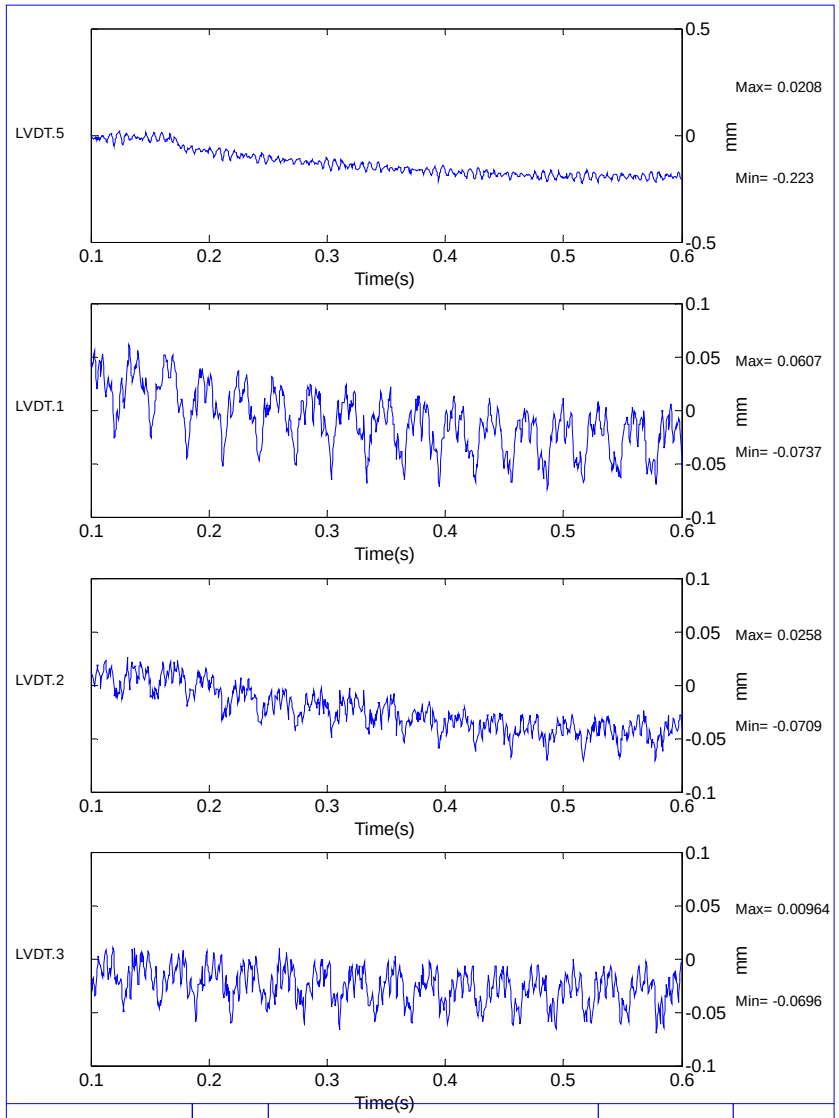


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	

23. Data from Test IT06, Earthquake 1.

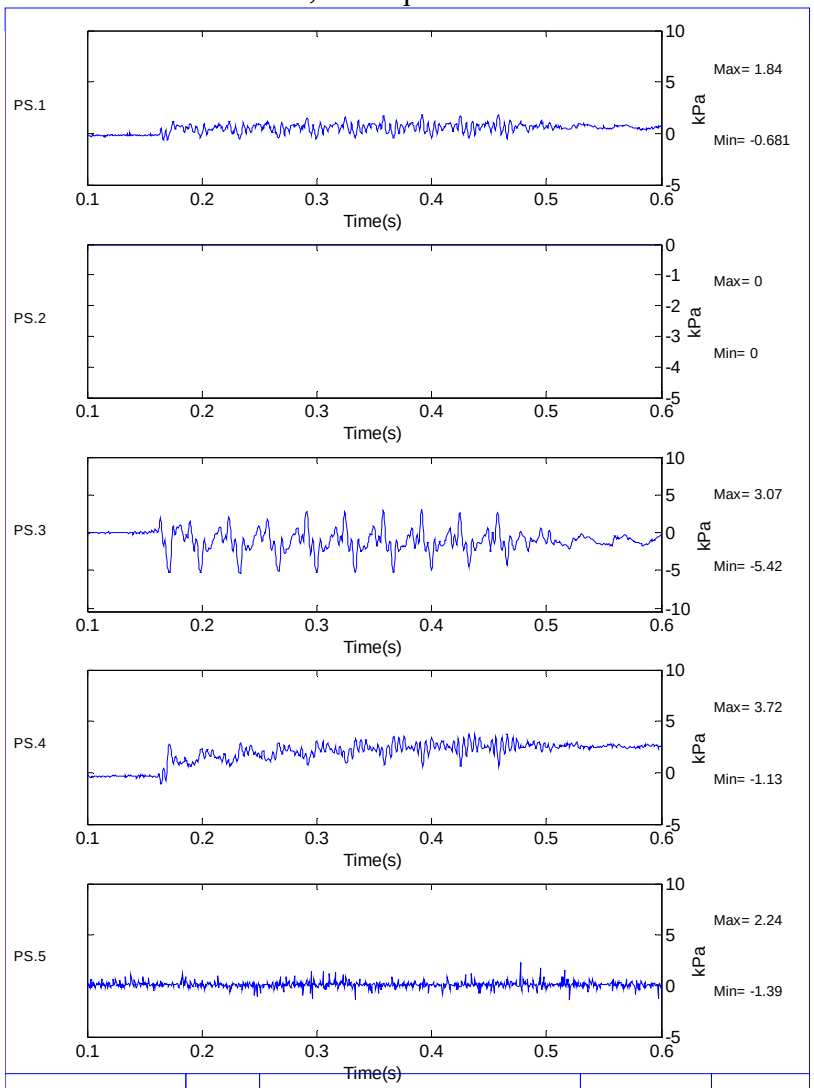


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	

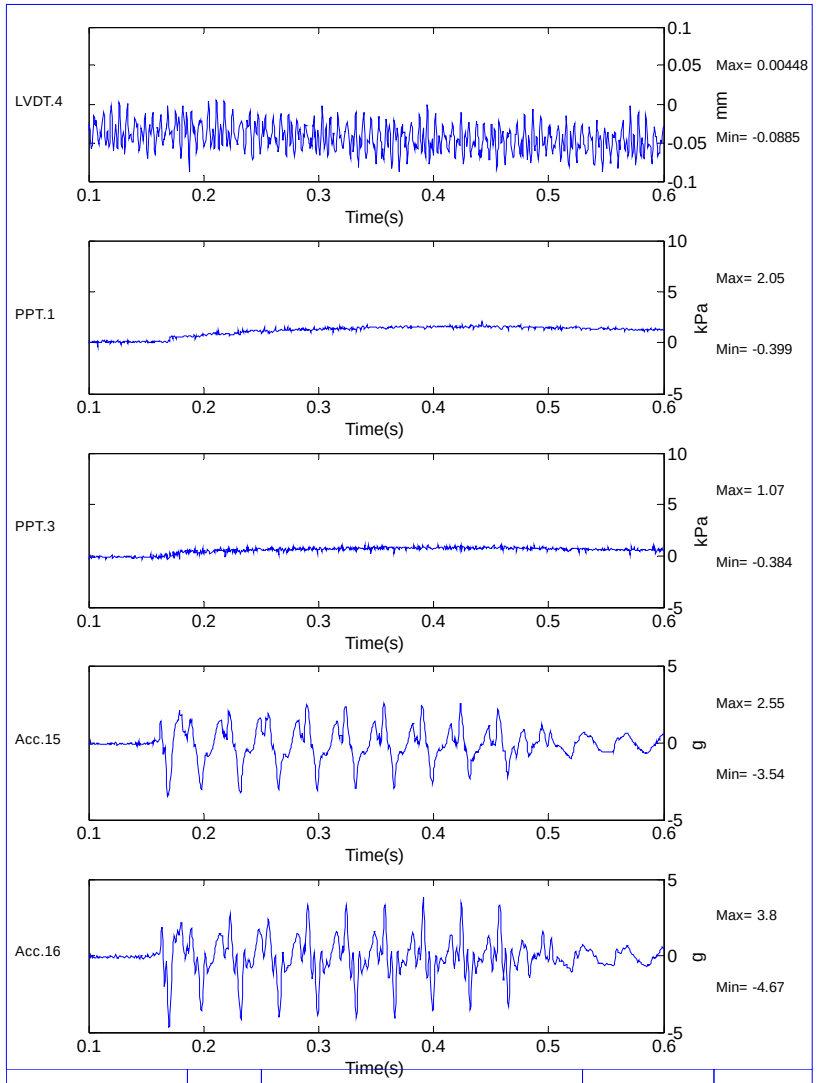


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	

24. Data from Test IT06, Earthquake 1.

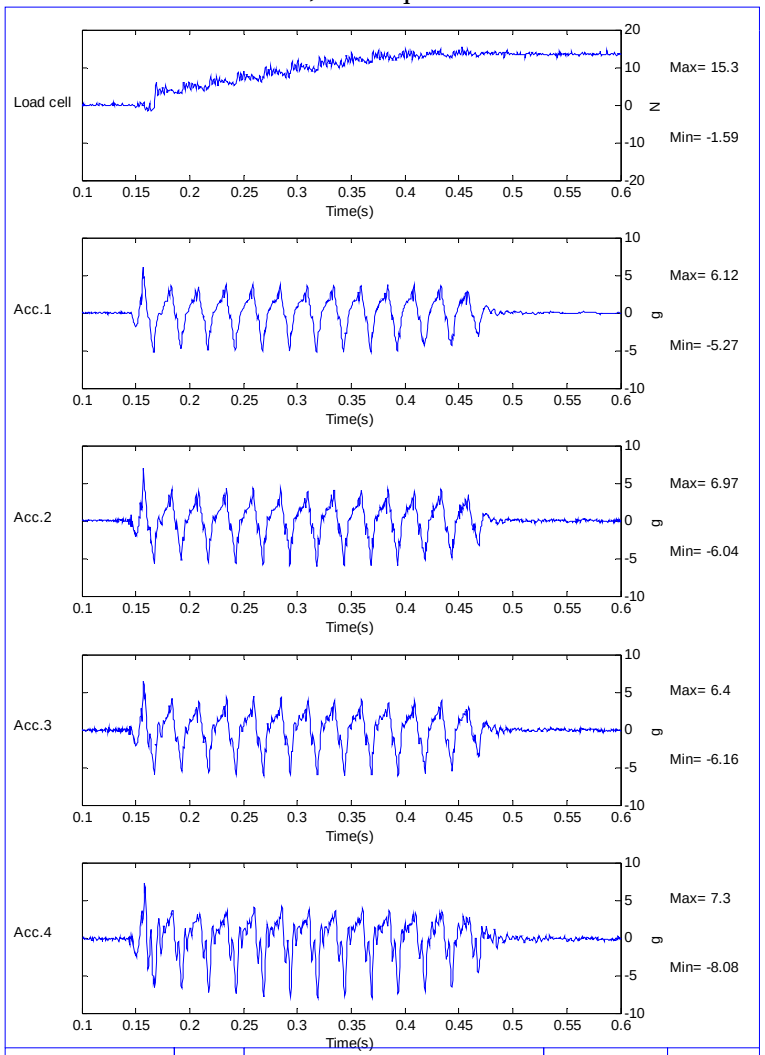


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	

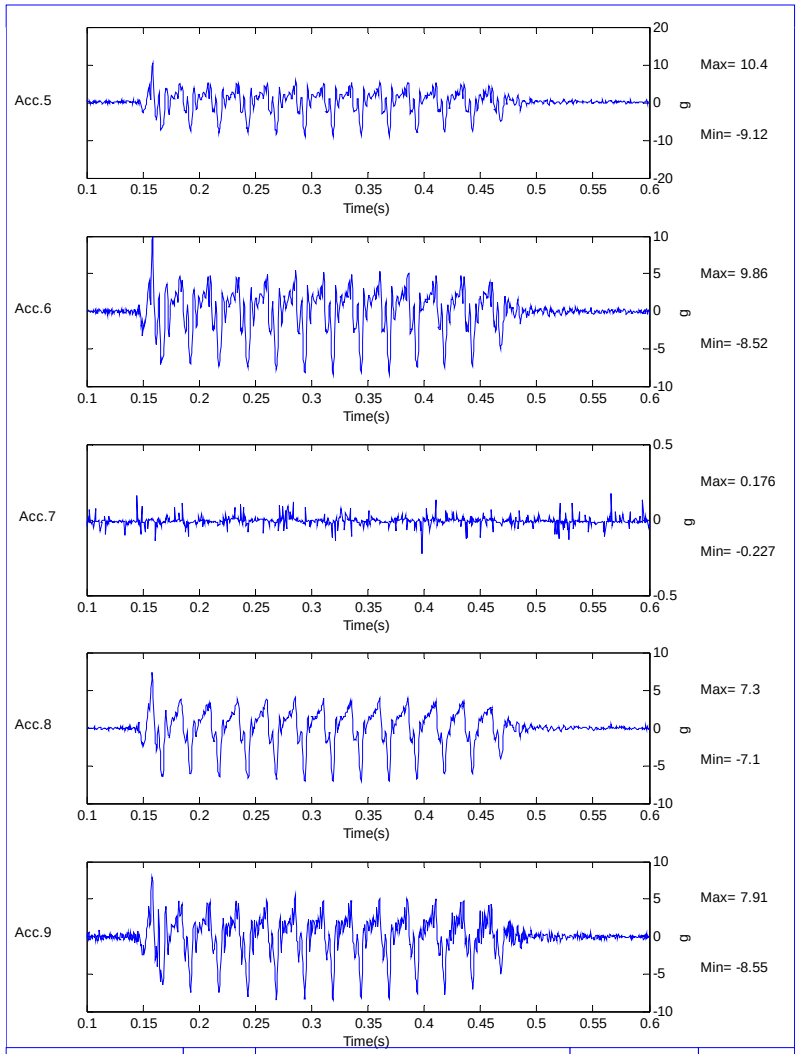


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	1	

25. Data from Test IT06, Earthquake 2.

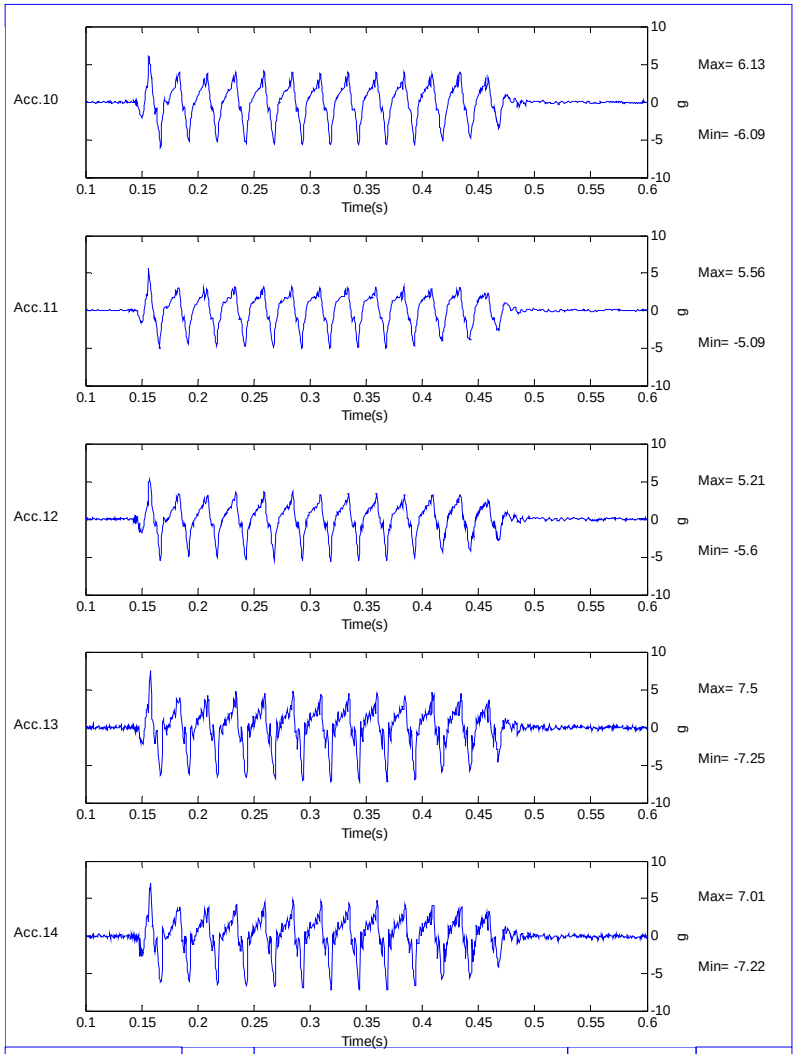


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

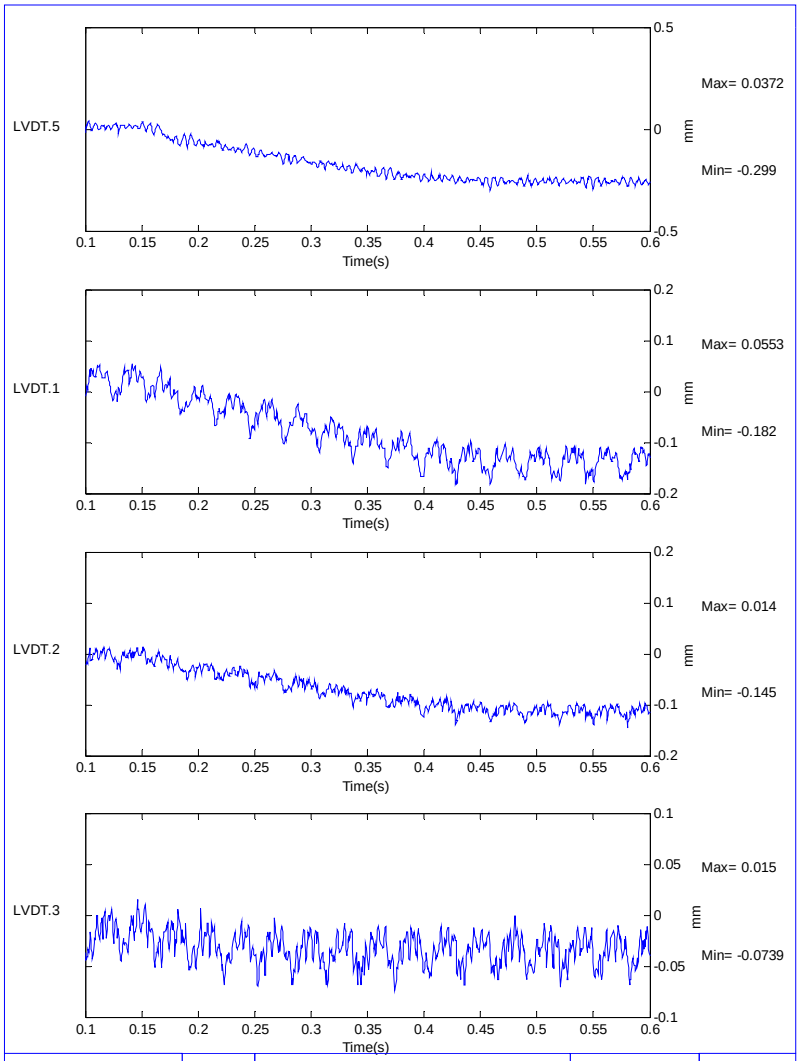


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

26. Data from Test IT06, Earthquake 2.

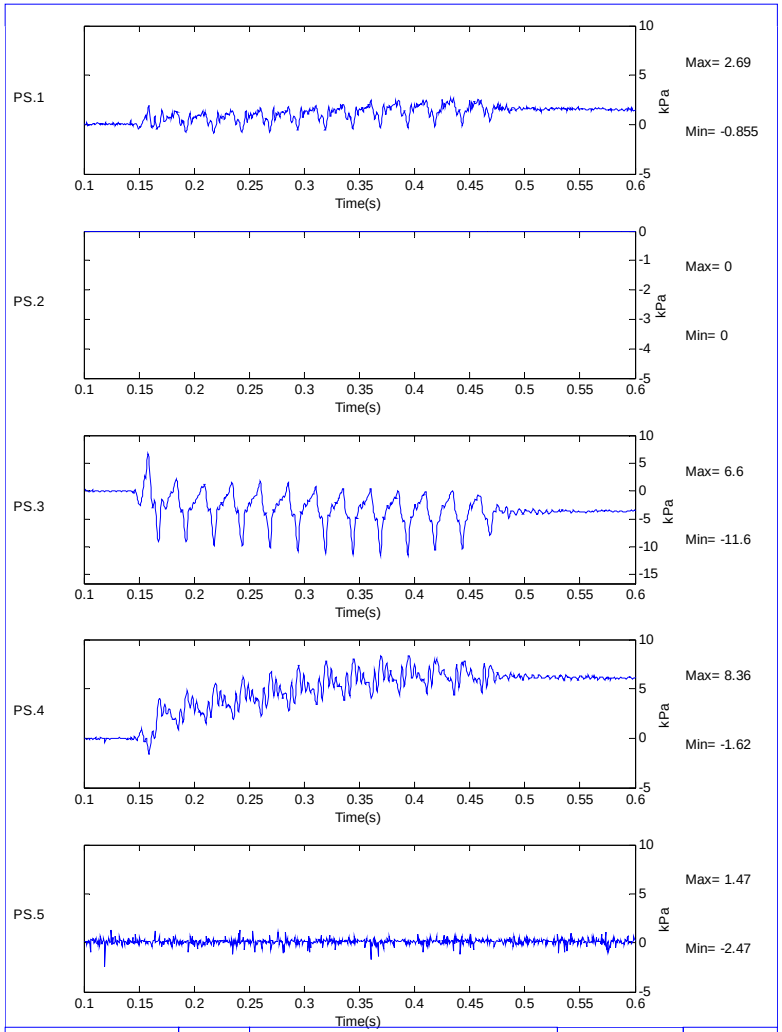


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

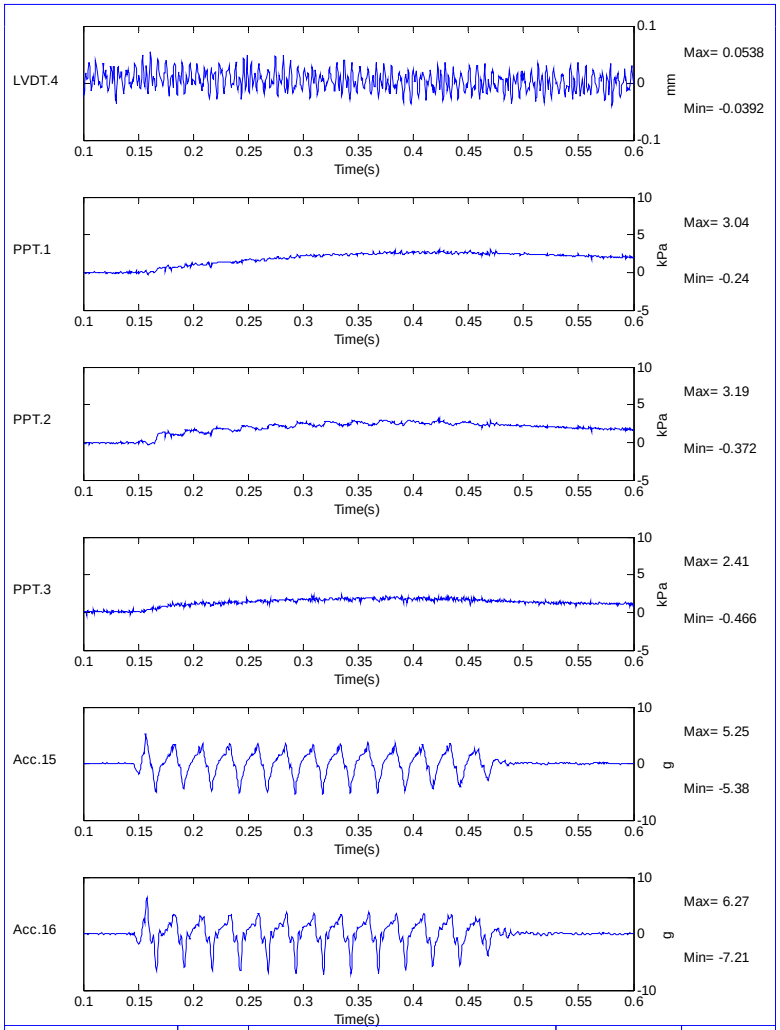


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

27. Data from Test IT06, Earthquake 2.

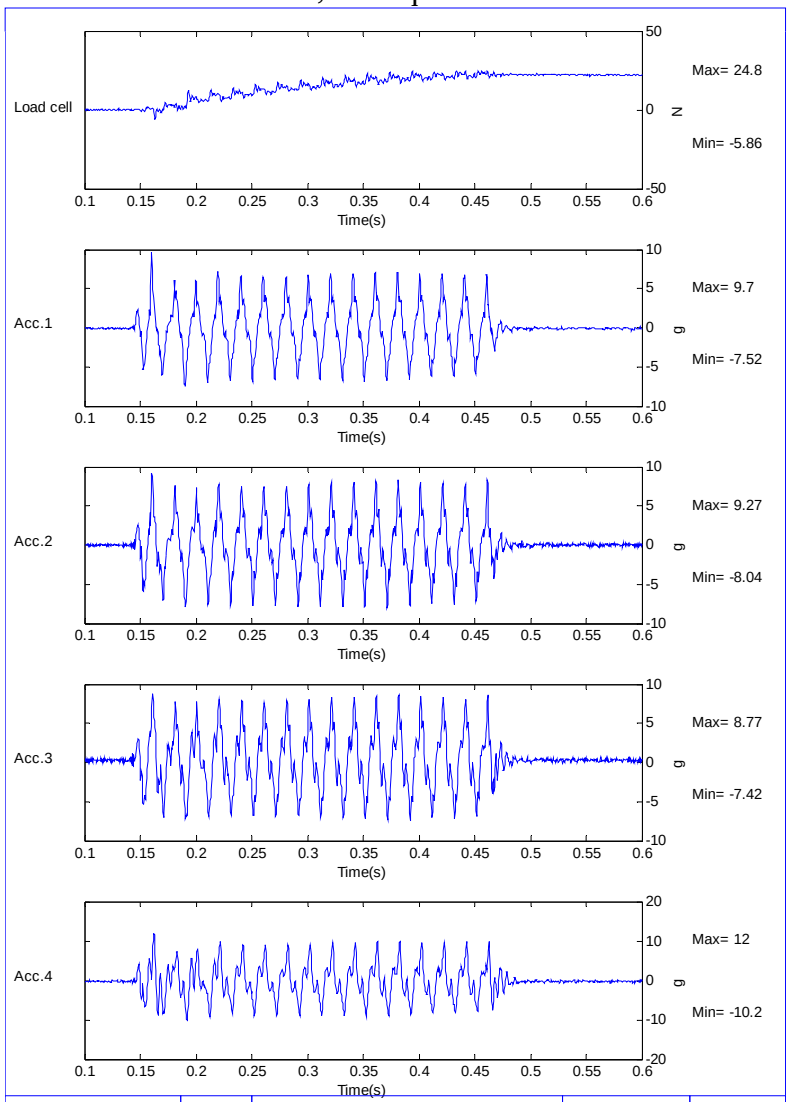


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

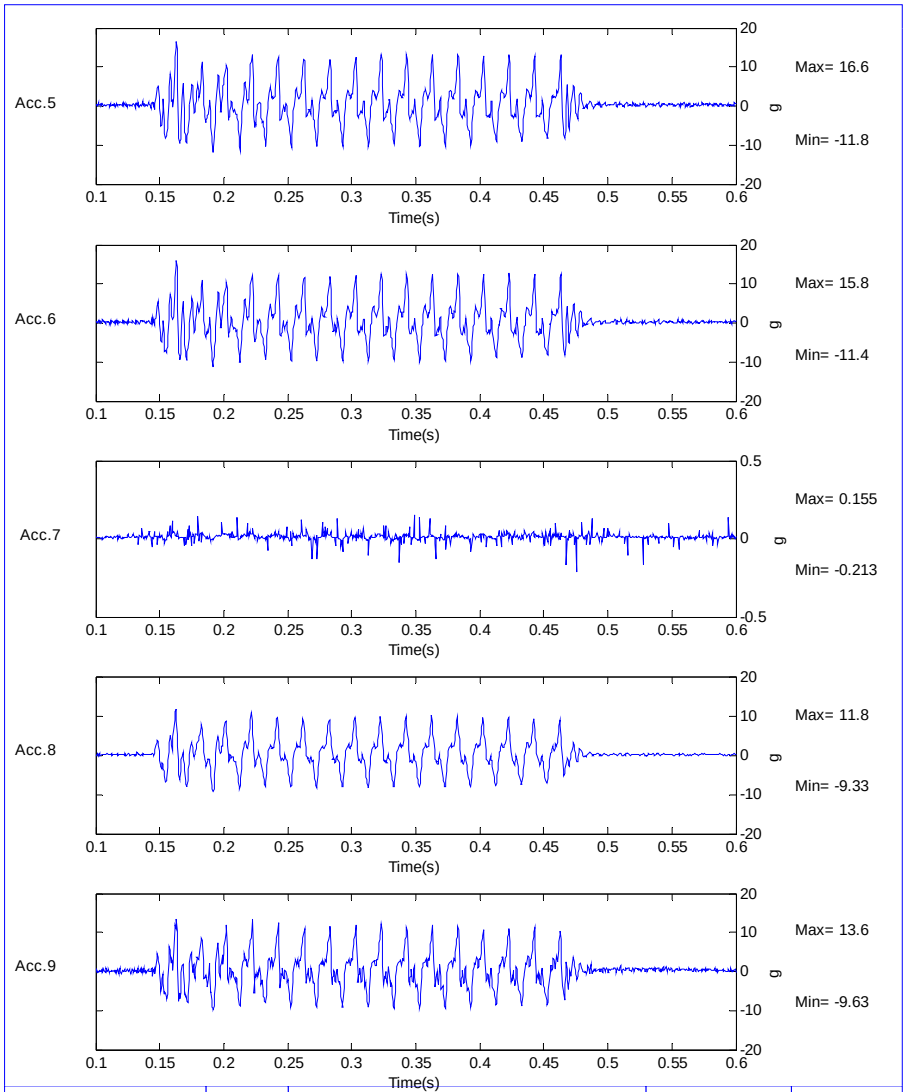


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	2	

28. Data from Test IT06, Earthquake 3.

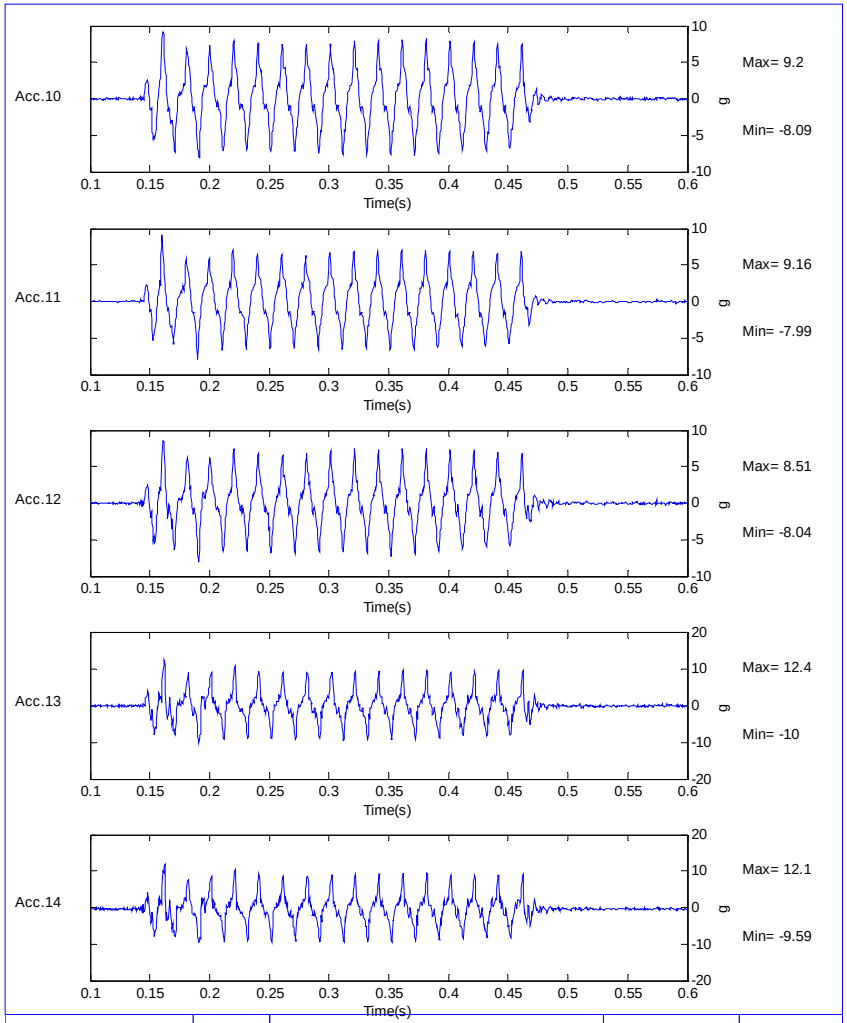


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

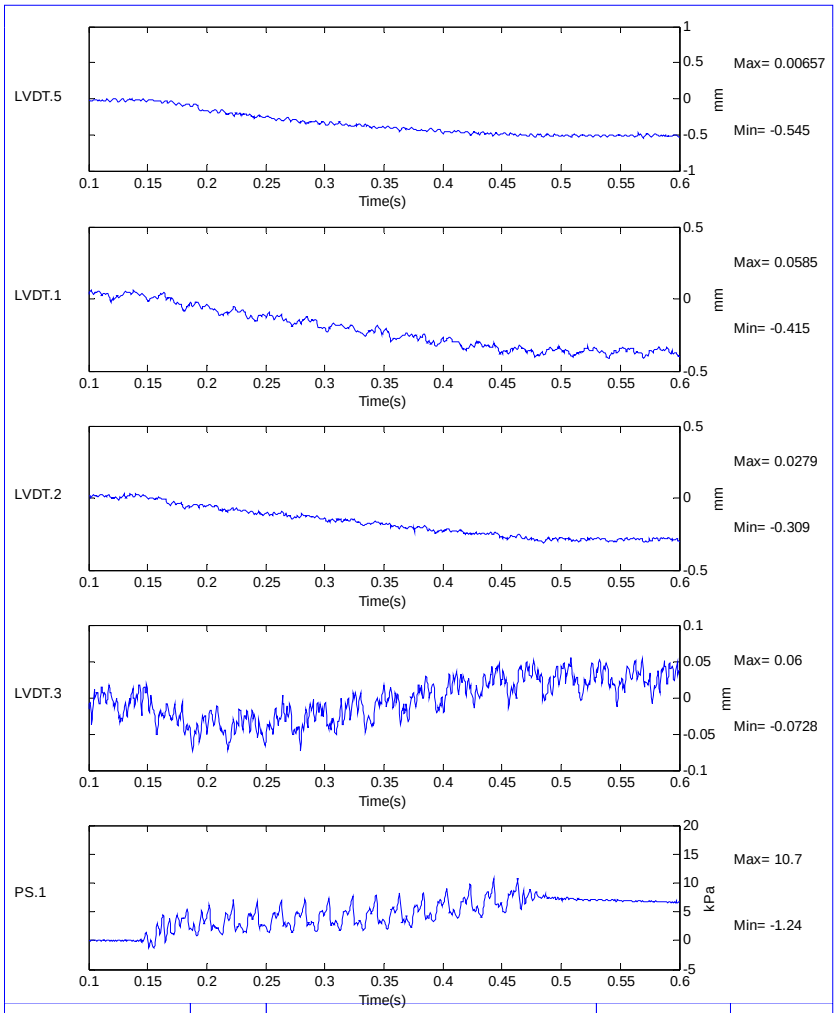


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

29. Data from Test IT06, Earthquake 3.

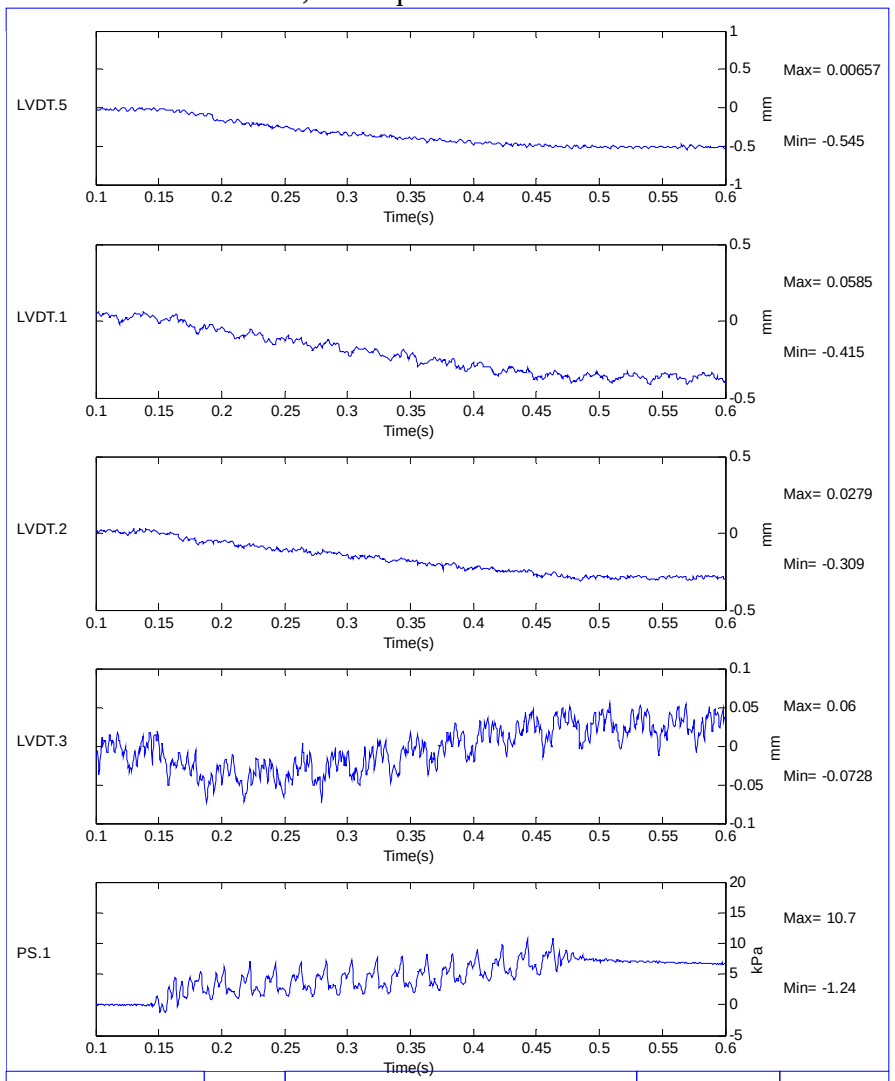


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

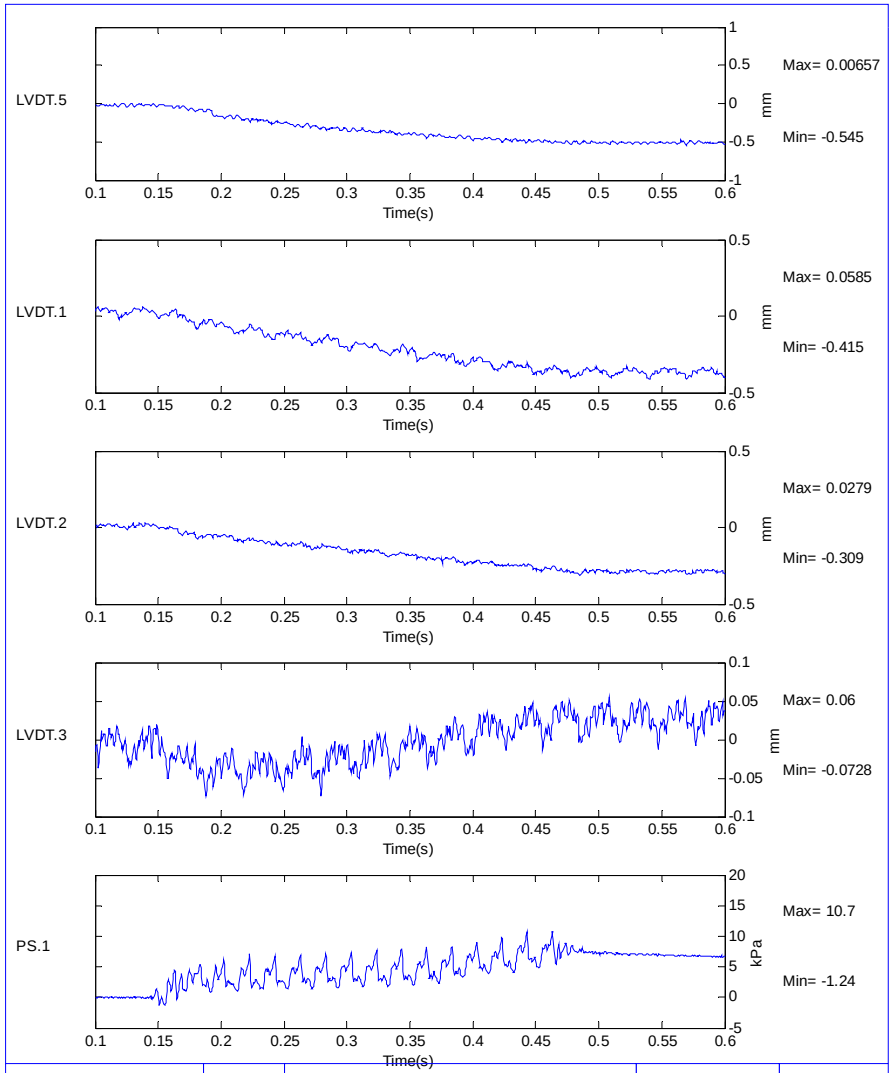


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

30. Data from Test IT06, Earthquake 3.

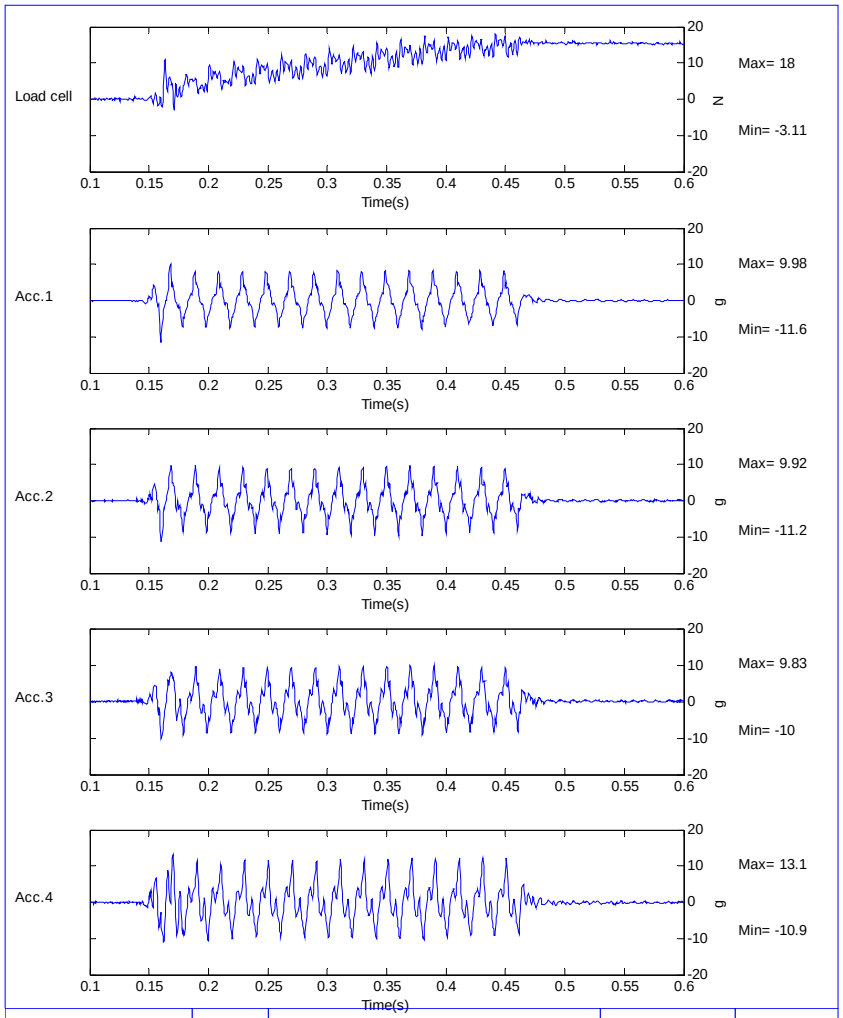


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

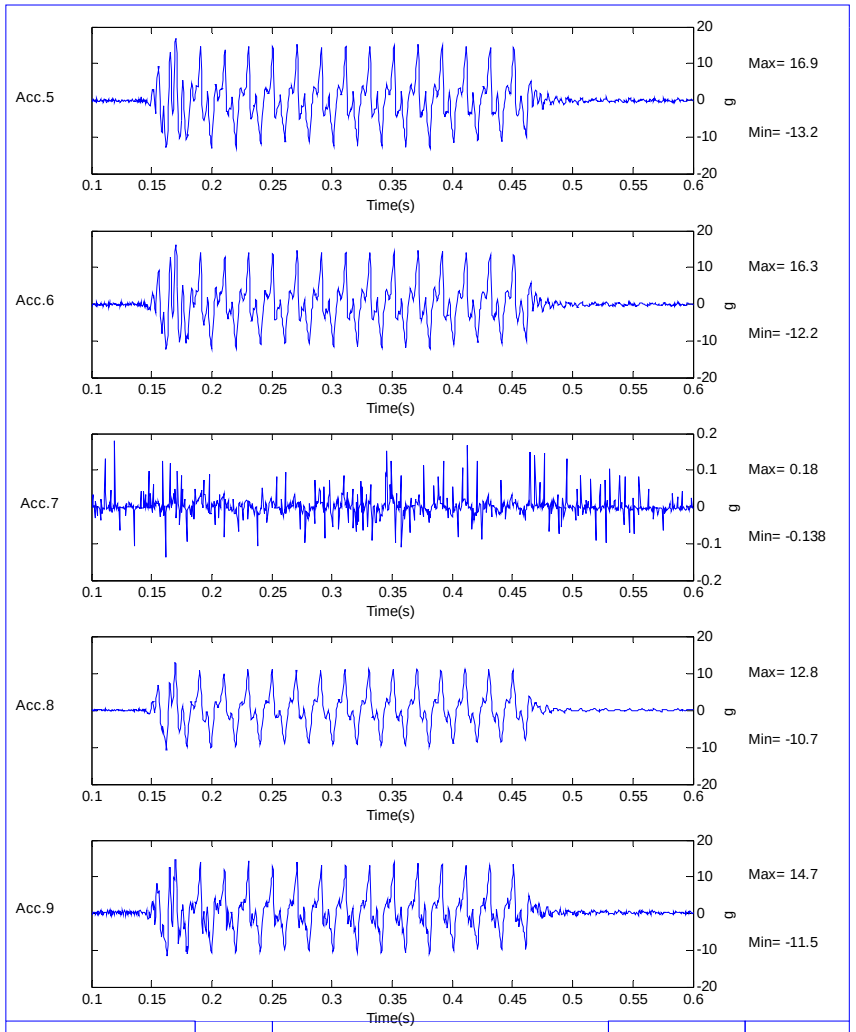


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	3	

31. Data from Test IT06, Earthquake 4.

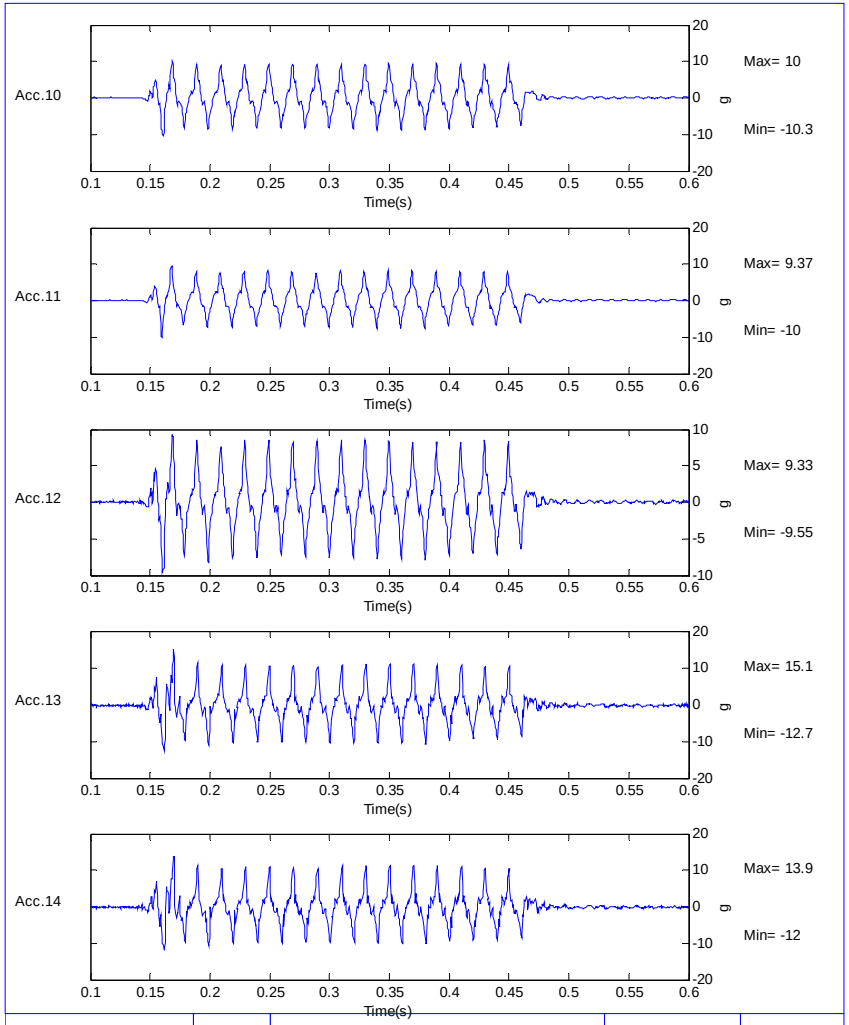


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

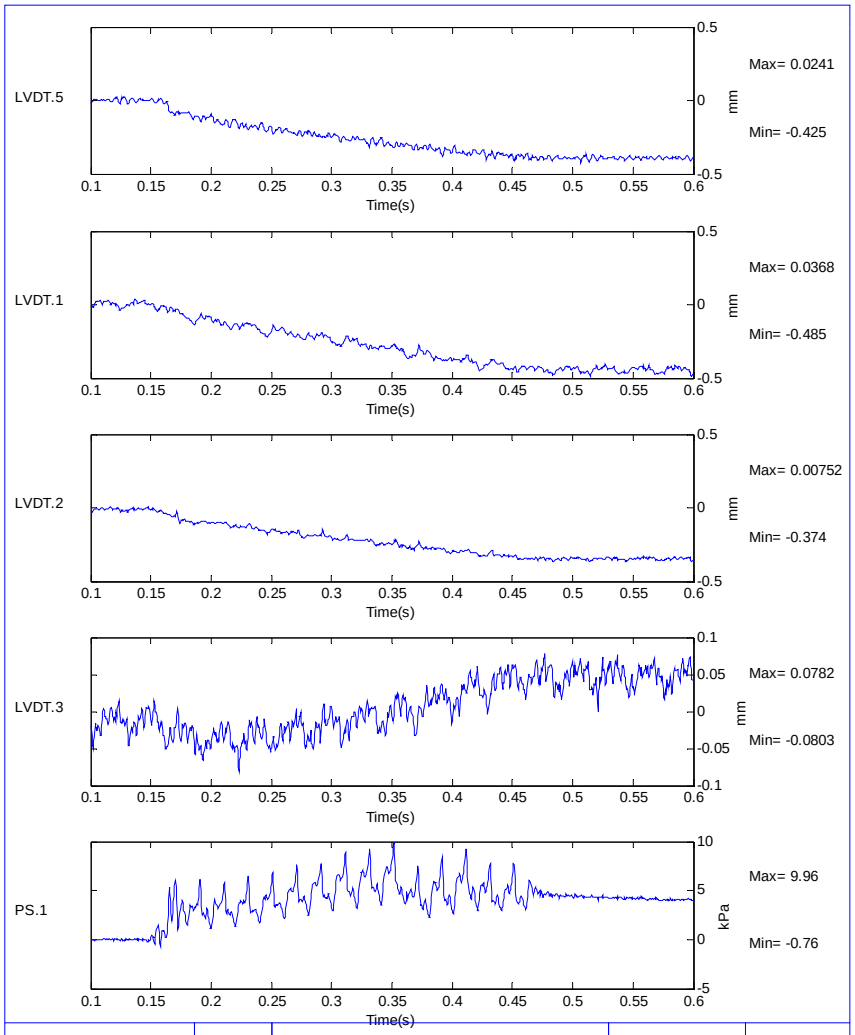


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

32. Data from Test IT06, Earthquake 4.

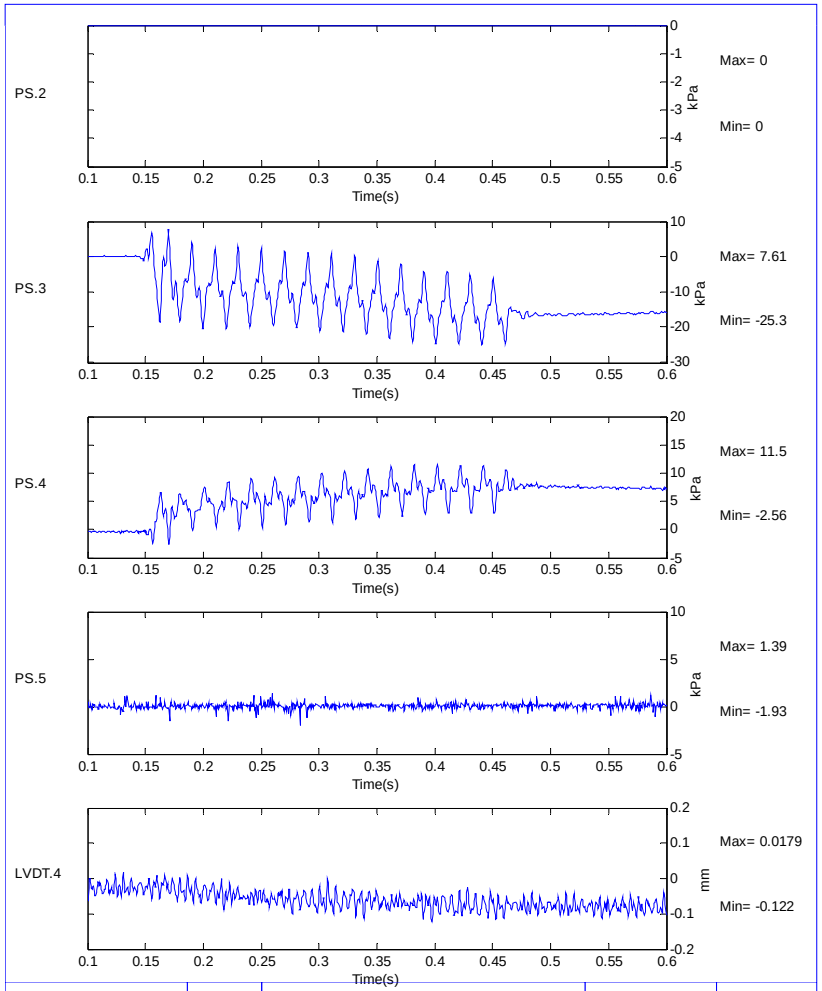


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

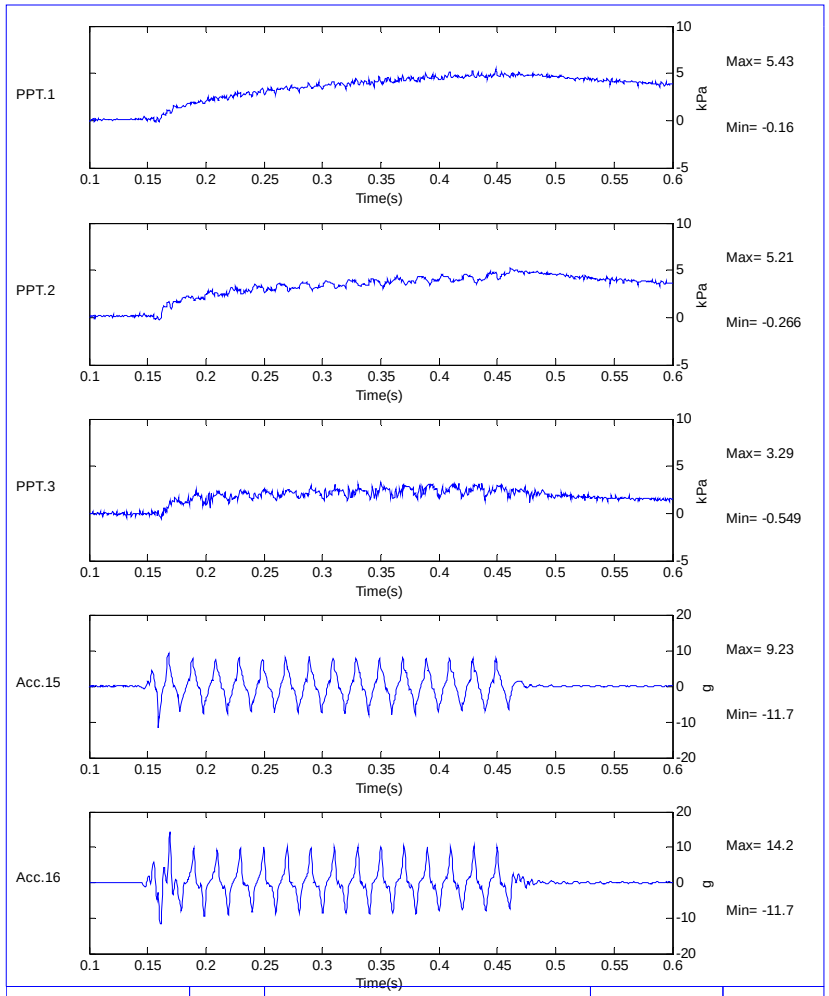


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

33. Data from Test IT06, Earthquake 4.

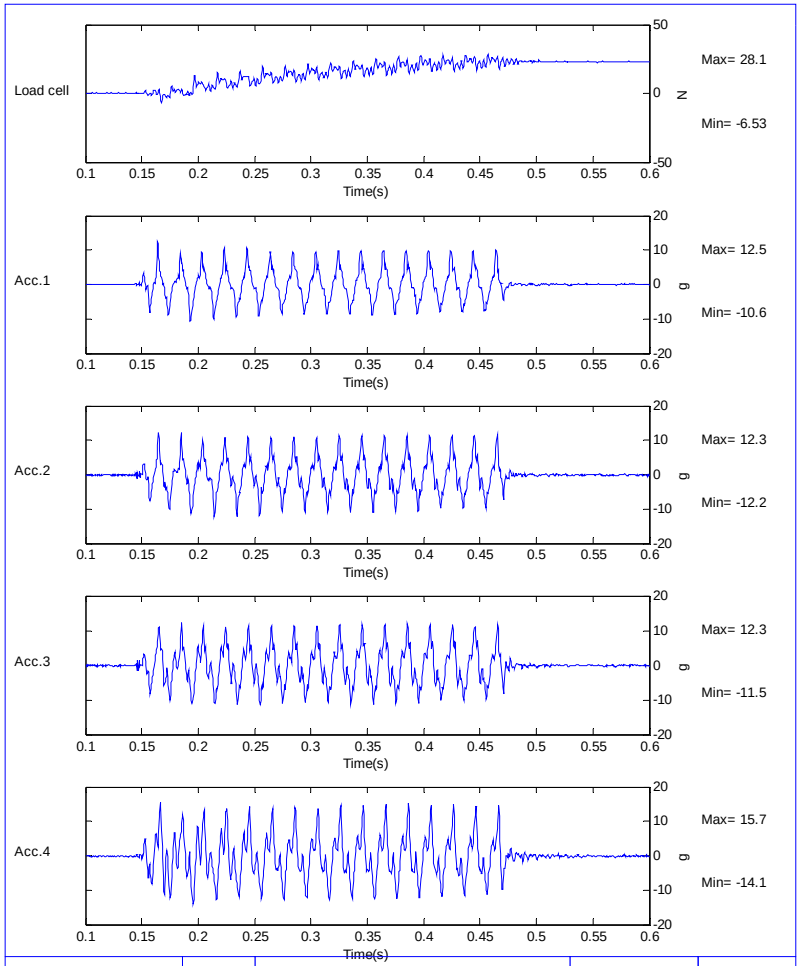


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

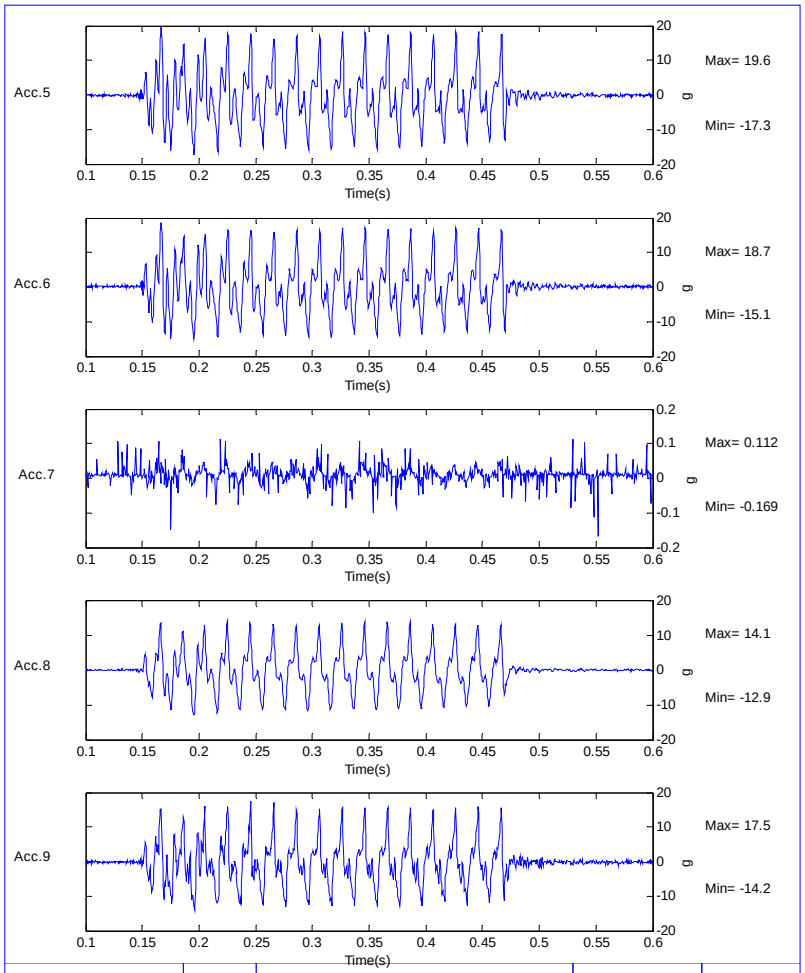


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	4	

34. Data from Test IT06, Earthquake 5.

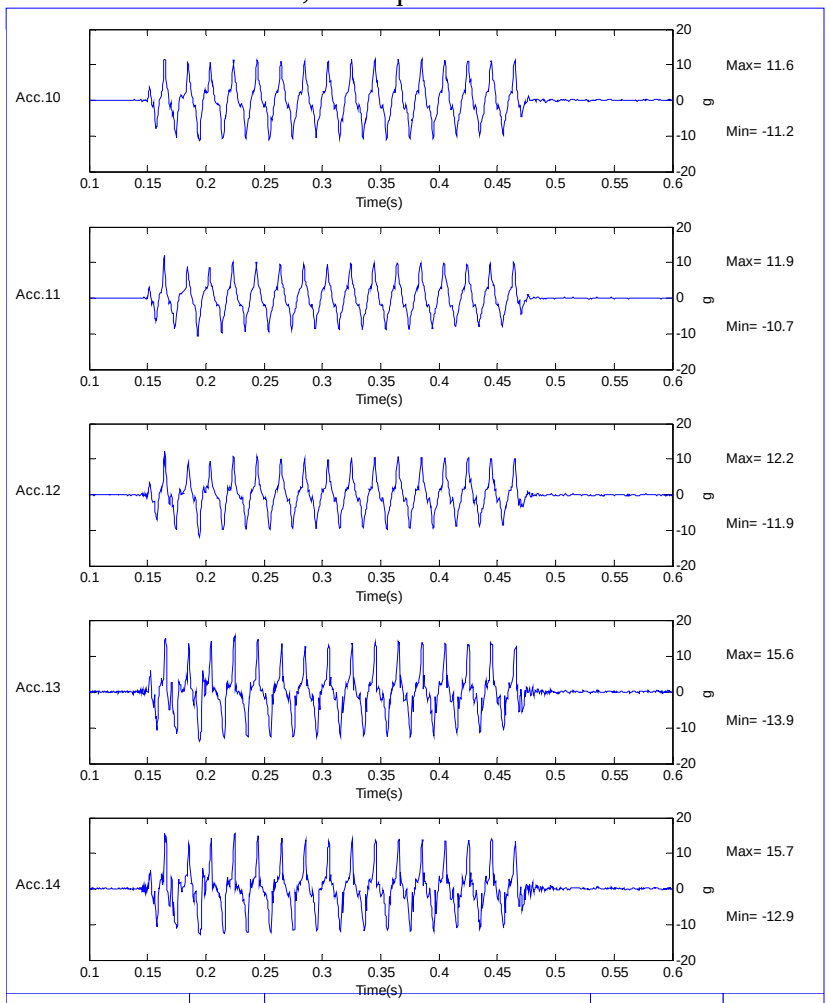


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

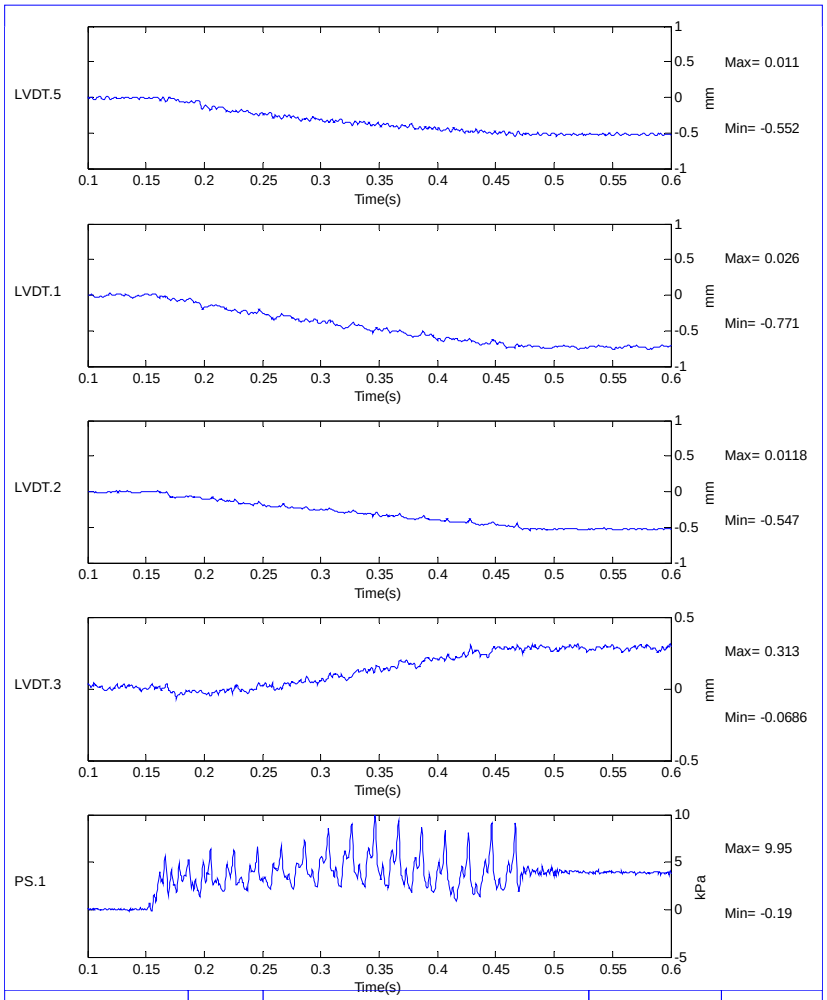


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

35. Data from Test IT06, Earthquake 5.

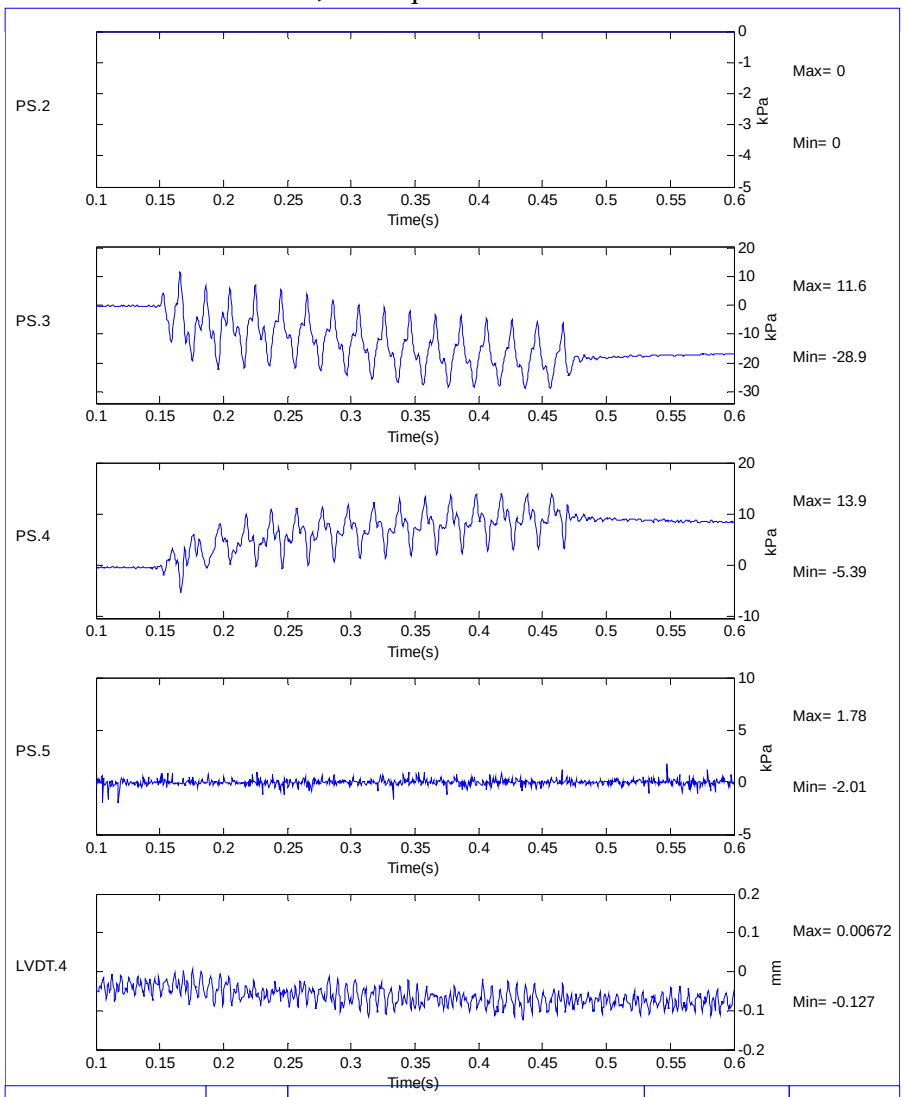


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

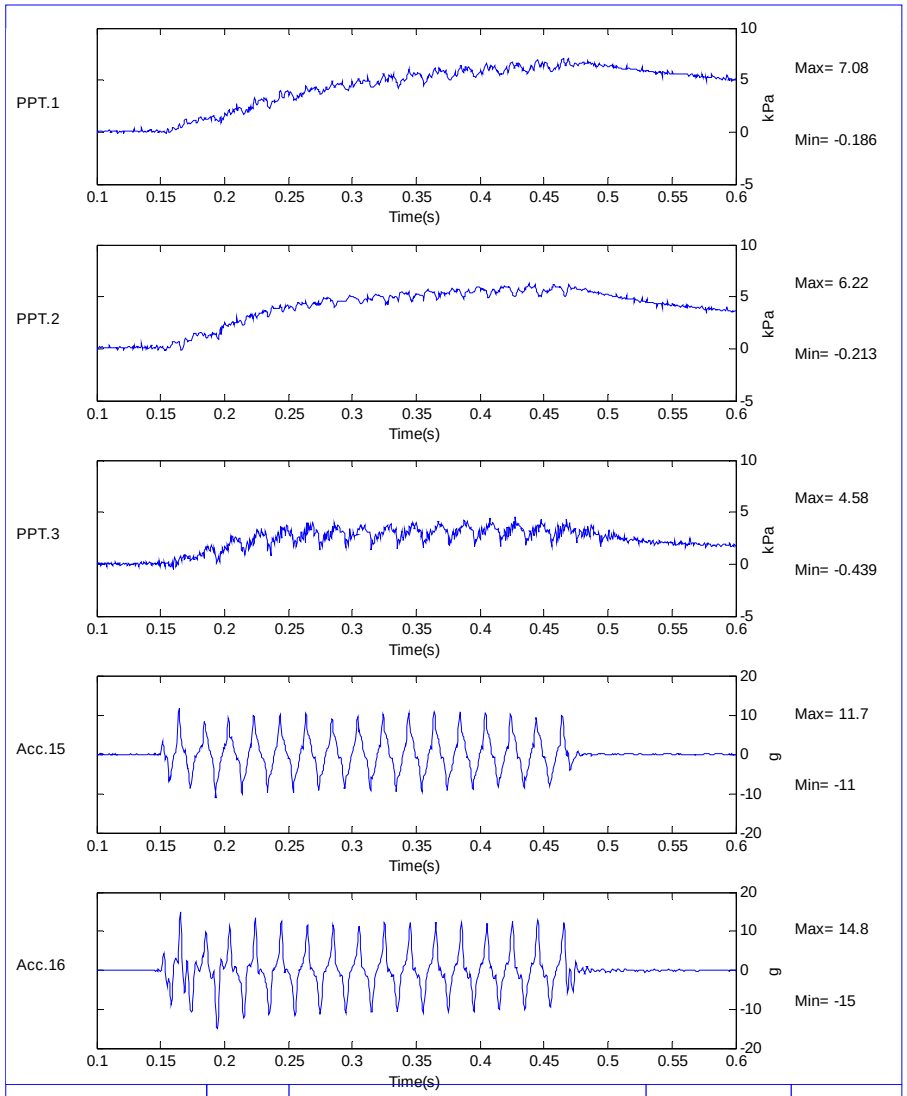


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

36. Data from Test IT06, Earthquake 5.

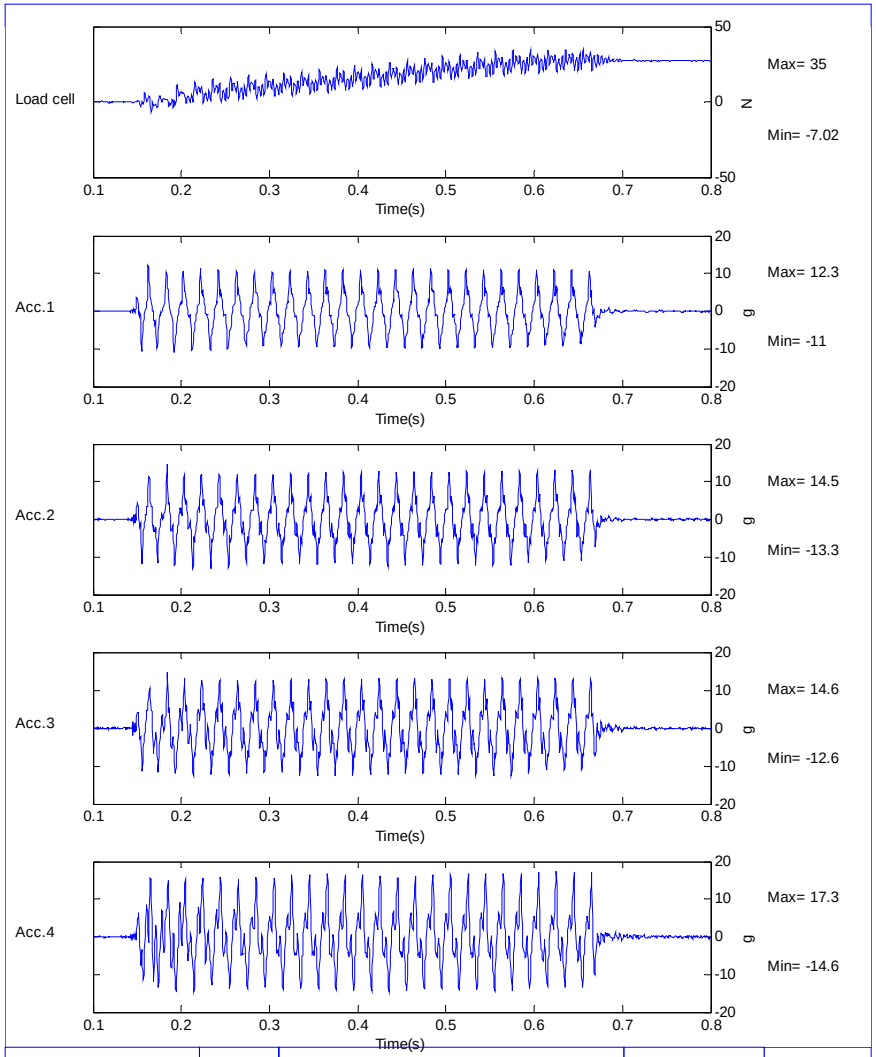


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

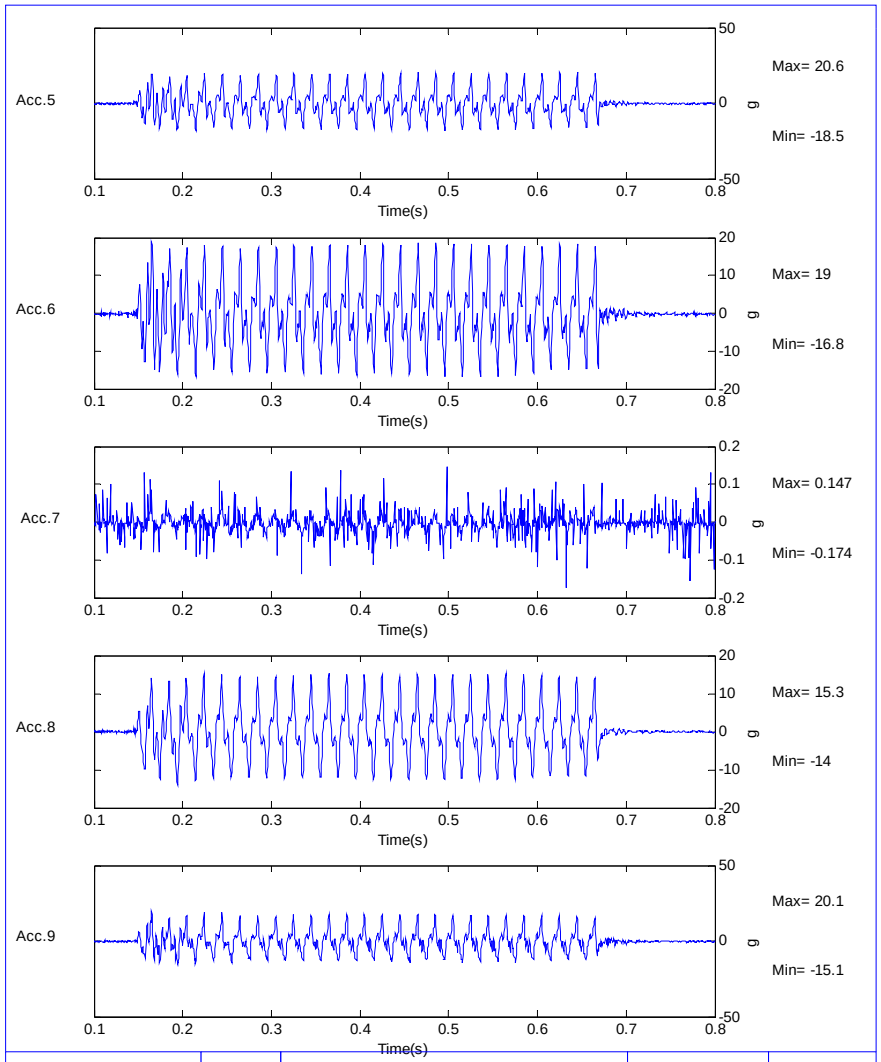


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	5	

37. Data from Test IT06, Earthquake 6.

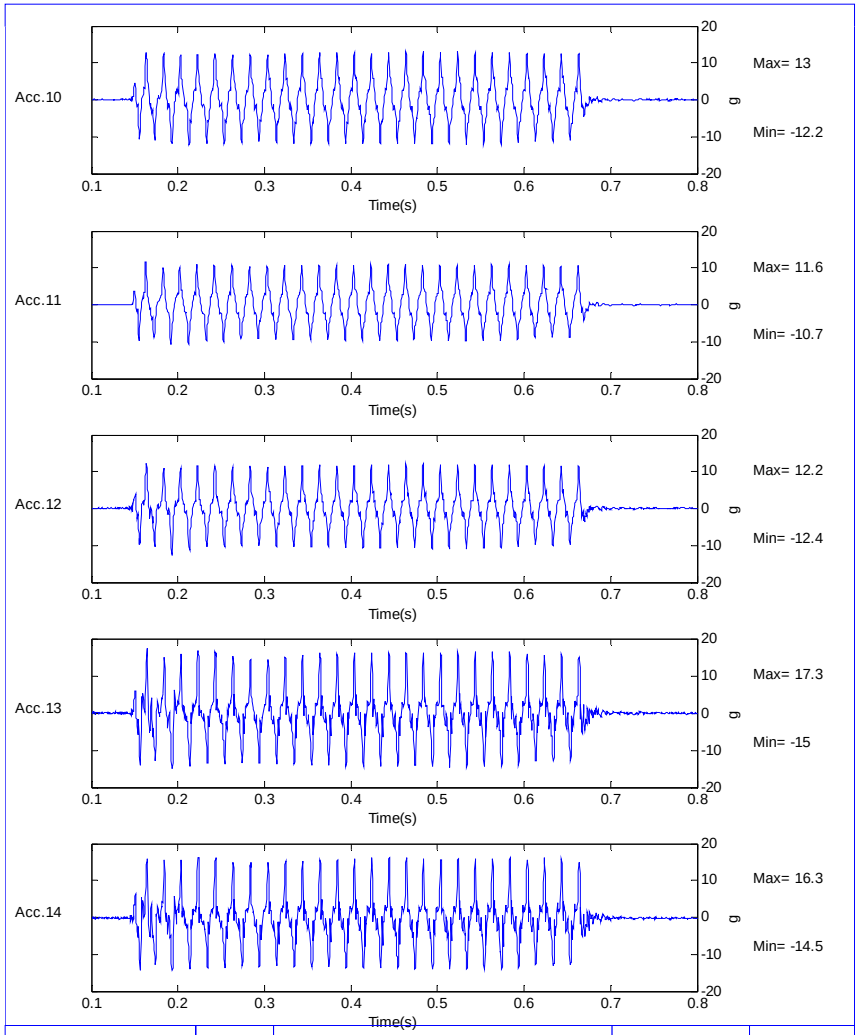


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	

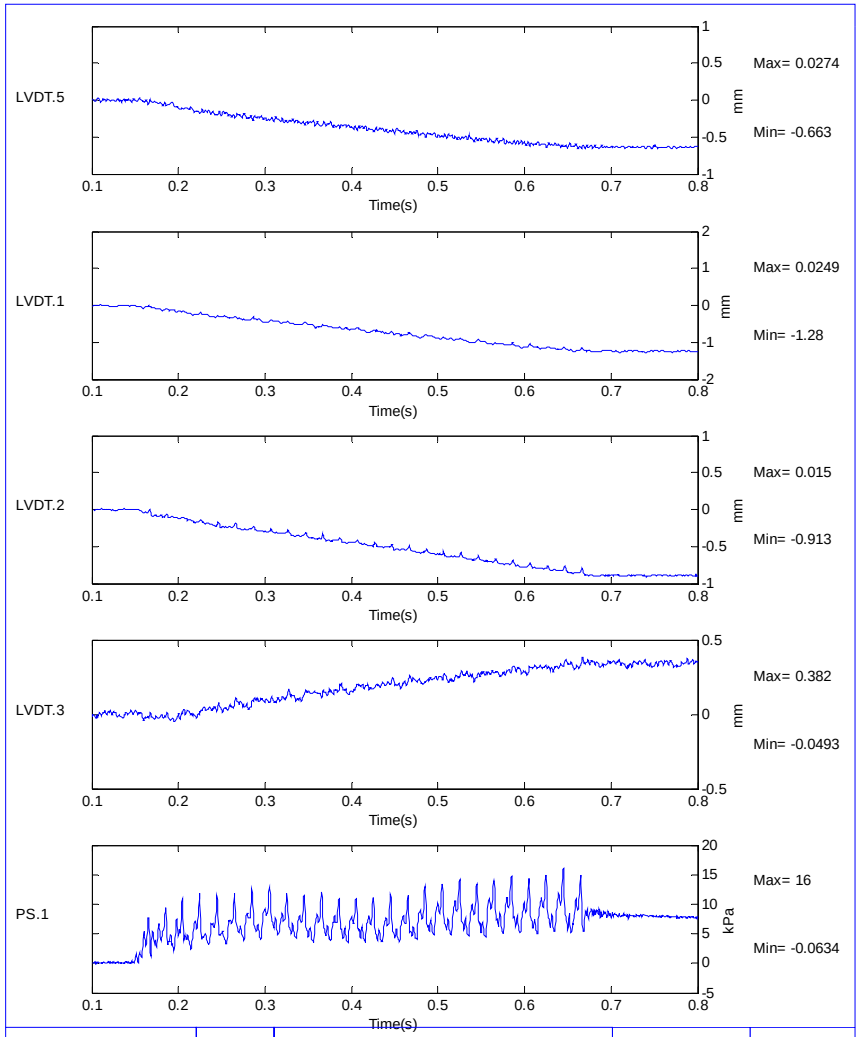


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	

38. Data from Test IT06, Earthquake 6.

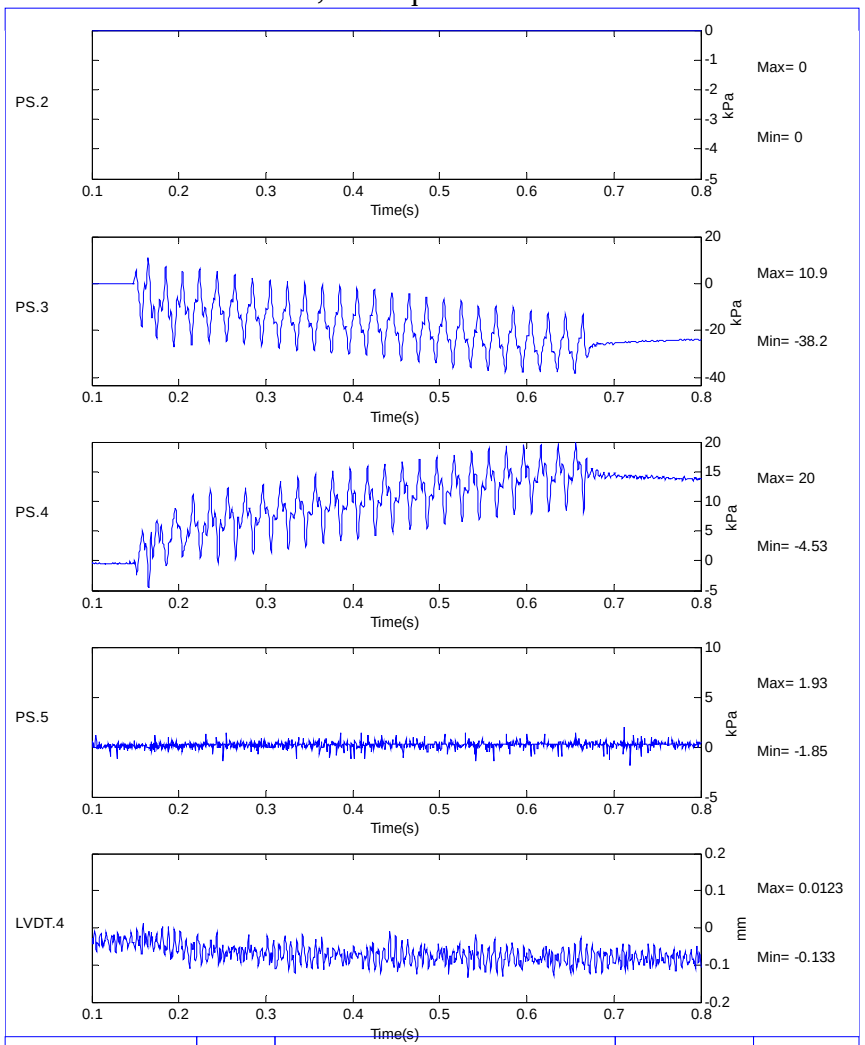


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	

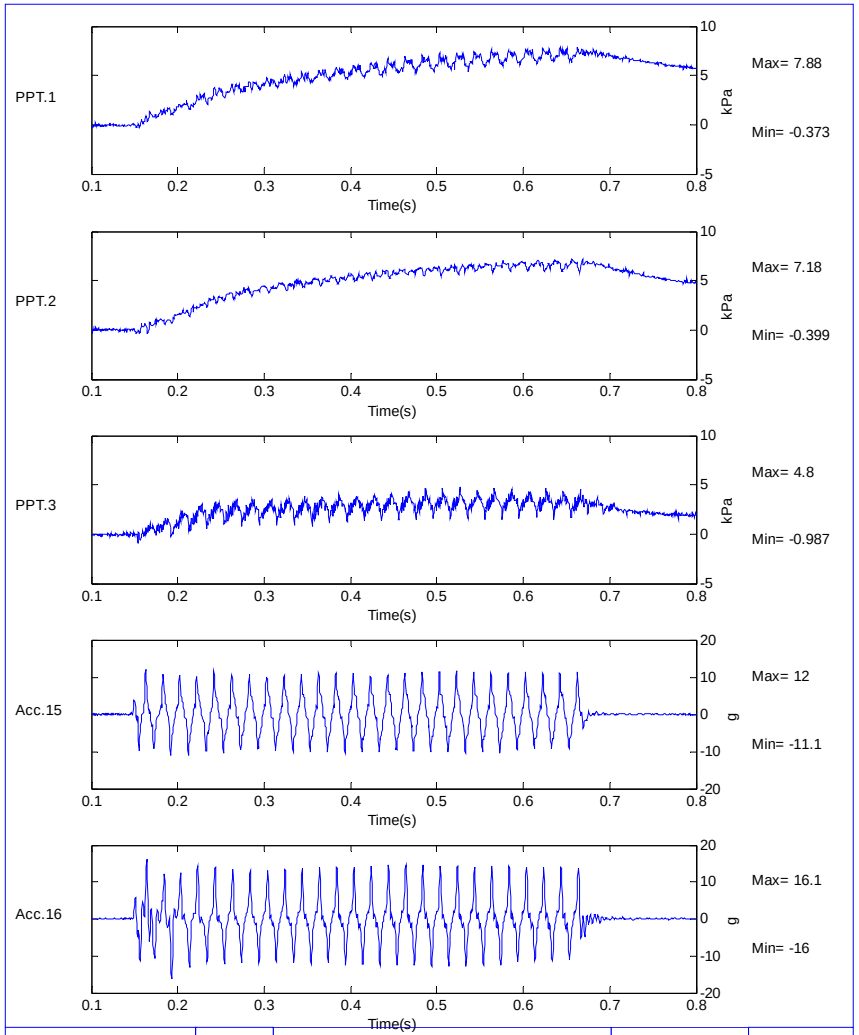


TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	

39. Data from Test IT06, Earthquake 6.



TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	



TEST		Scales: Model Unfiltered Data	Earthquake	Figure No.
FLIGHT 1		Short-Term Time Records	6	