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EARTHQUAKE-INDUCED LIQUEFACTION OF CONFINED SOIL ZONES: A CENTRIFUGE STUDY

FINAL TECHNICAL REPORT

by

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16th November 1992

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Contractor	Andrew N Schofield and Associates Ltd. 9 Little St Mary's Lane, Cambridge
Contract Number	DAJA45-92-C-0022
ANS&A Report Number	26-04-R-03
Monitoring Agency Number	R & D 6878-EN-01

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

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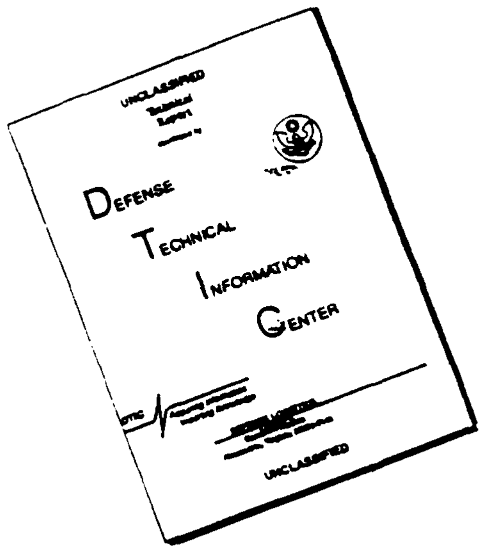

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
16 - NOV - 1992

3. REPORT TYPE AND DATES COVERED
FINAL TECHNICAL JULY TO NOV 1992

4. TITLE AND SUBTITLE
EARTHQUAKE INDUCED LIQUEFACTION OF CONFINED SOIL ZONES, A CENTRIFUGE STUDY

5. FUNDING NUMBERS

6. AUTHOR(S)
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ANDREW N SCHOFIELD AND ASSOCIATES LTD
9 LITTLE ST MARY'S LANE
CAMBRIDGE CB2 1RR ENGLAND

8. PERFORMING ORGANIZATION REPORT NUMBER
26-04-R-03
DAJA45-92-C-0022

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAE WATERWAYS EXPERIMENT STATION
BOX 631
VICKSBURG MS 39180-0631

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
R&D 6878-EN-01

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

See "Introduction"

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

93-01868

103,05

93 2 1 084

EARTHQUAKE-INDUCED LIQUEFACTION OF CONFINED SOIL ZONES: A CENTRIFUGE STUDY

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1 Introduction

Embankments and Levee's form an important civil engineering construction and are widely used for supporting transportation lines, construction of earthen dams, dykes to protect low lying areas etc.,. Construction of a levee is carried out by compacting layers of soil excavated from close by borrow pits. Due to the construction methods employed in the field, it is possible for a small loose pocket to be present within a densely compacted embankment. If the water table is shallow, the embankment may be under saturated conditions. The seismic behaviour of such an embankment is the subject of the present study.

During an earthquake the saturated soil is subjected to a rapid cyclic shear stress variation. This leads to densification of an initially loose soil element causing the pore pressure to increase. If undrained conditions are assumed during the earthquake loading the increase in pore pressure is translated into a lowering of the effective stress. This results in liquefaction conditions when the excess pore pressure equals the total stress. Presence of such a liquefied zone in an embankment may result in slipping of the slope of embankment.

In this report a series of dynamic centrifuge tests conducted on sand embankments with loose pockets of sands enclosed in them will be discussed. New modelling techniques to prepare a loose pocket of sand were investigated in the first series of experiments. In this series two centrifuge tests were conducted in which fine Nevada sand was poured loosely into a one dimensional freezing box and was saturated with water. The model was then frozen so that the loose section of the model is not compacted during the model preparation phase and transportation of the centrifuge model on to the arm of the centrifuge.

A second series of centrifuge tests were conducted in which 80 cS silicone oil was used as the pore fluid. This model fluid will simulate the inertial effects as well as the diffusion processes like consolidation correctly. Schofield (1981). during a centrifuge test conducted under '80' gravities.

In this report the facilities available at the Cambridge Geotechnical Centrifuge Centre will be discussed. The instrumentation used in the centrifuge tests is out lined. The materials used in the centrifuge tests will be described. The centrifuge test procedure and the presentation of test data will be explained next. The model preparation adopted for each test and the data acquired during the test will be presented seperately for each test. Some conclusions drawn from the test series will be presented at the end.

2 Facilities

2.1 Cambridge Geotechnical Centrifuge Centre

The beam centrifuge at the Cambridge Geotechnical Centrifuge Centre has an effective radius of about 4.0 metres and a maximum testing gravity of 155 g and is a 150 g-ton machine. The centrifuge chamber has a diametre of 10 metres. The beam centrifuge was commissioned in 1975 and over 1100 model tests were carried out using this facility. The operation of the beam centrifuge has been described by Schofield (1980).

2.2 Bumpy Road Earthquake Actuator

The model earthquakes in the centrifuge tests conducted in this series were generated by the Bumpy Road Actuator. The details of the earthquake actuating system were described by Kutter (1983). The schematic diagram of the actuator is presented in Fig.1. A duraluminium box which holds the model embankment is suspended on a pair of flexible straps which enable the lateral movement during a model earthquake. There is a toothed rack fixed to the base of the strong box which engages with a counter part on the bumpy road actuator. A sinusoidal track on which 10 cycles are machined is fixed firmly to the wall of the centrifuge chamber. An earthquake can be triggered at the desired time by controlling the pressures across a double acting piston which makes a wheel on the actuator to come into contact with the sinusoidal track (see Fig.1). The radial movement of the wheel is translated into lateral movement of the base of strong box by a bell-crank mechanism. Since the earthquake actuator was put into operation in 1981 about 1400 earthquakes events have been recorded on a wide range of models.

2.3 Strong box

The model container is a strong and stiff box made of duraluminium. The inside dimensions of the box are 0.9 m × 0.48 m × 0.22 m and for an 80g centrifuge test these dimensions correspond to dimensions of a soil body of 72 m × 38.4 m × 19.6 m. The maximum pay load allowed for a dynamic test is just below 300 kg for a 80g test. This corresponds to a soil weight of about 100.000 tons in the prototype.

3 Instrumentation

3.1 Accelerometers (ACC)

In the centrifuge tests reported here miniature piezoelectric accelerometers manufactured by D.J.Birchall were used to measure the accelerations in the soil as well as the input acceleration of the strong box. The device has a resonant frequency of about 50 kHz and a maximum error of 5 %. The weight of the transducer is about 20 grams. Fig.2a shows the dimensions of the accelerometer. The accelerometers embedded in the soil were sealed with silicone rubber.

The accelerometers were caliberated before each test by subjecting them to a saturated '2g' acceleration and measuring the output generated on a cathode ray oscilloscope. The caliberation constant for each accelerometer was expressed in the units of 'V/g'.

3.2 Pore pressure transducers (PPT)

Pore pressures in the saturated soil were monitored by Druck PDCR 81 pore pressure transducers. This type of pore pressure transducers have a linear range upto 300 kPa and weigh about 10 grams. The corner frequency of the dynamic response of the transducer is 15 kHz. The maximum error is 0.2 %. In the centrifuge tests reported here, the active diaphram of the PPT is covered with a porous brass stone. The dimensions of the PPT are presented in Fig.2b.

All the pore pressure transducers were caliberated by applying standard water pressures on the active diaphram. The output generated by the device was measured using a digital voltmeter and caliberation constant was obtained in the units of 'kPa/mV'.

4 Materials

4.1 Sand

Two grades of sand were used in the centrifuge tests reported here.

4.1.1 LB 52/100 sand

Leighton Buzzard 52/100 medium dense sand was used to construct the dense section of the levee of all the centrifuge models. The nominal size of this sand is 0.225 mm. The specific gravity of the sand is 2.65 and the maximum and minimum void ratio's are 0.98 and 0.585 respectively. This sand was supplied by D.J.Ball and Co., Colworth and was employed in many a centrifuge tests conducted in Cambridge. The grain size distribution of LB 52/100 sand is shown in Fig.3a.

4.1.2 Nevada sand

The loose pocket of the levee was constructed by using fine grained Nevada sand. The specific gravity of this sand is 2.68 and the maximum and minimum void ratio's were 0.894 and 0.516 respectively. This sand was supplied by Earth Technology corporation and the laboratory tests on these sands were reported by them.

4.2 Silicone oil

The pore fluid used in the centrifuge tests GEM 3 to 6 was silicone oil. The viscosity of this oil was 80 centistokes in all of these centrifuge tests. A centrifuge model saturated with high viscosity pore fluid satisfies the dynamic time scale relationship and the consolidation time rate effects simultaneously.

4.3 Water

Water was used as pore fluid in centrifuge tests GEM-1 and 2. The loose section was sustained in that state by freezing the section. Hence water was used as the pore fluid. Deionised water was used for these tests.

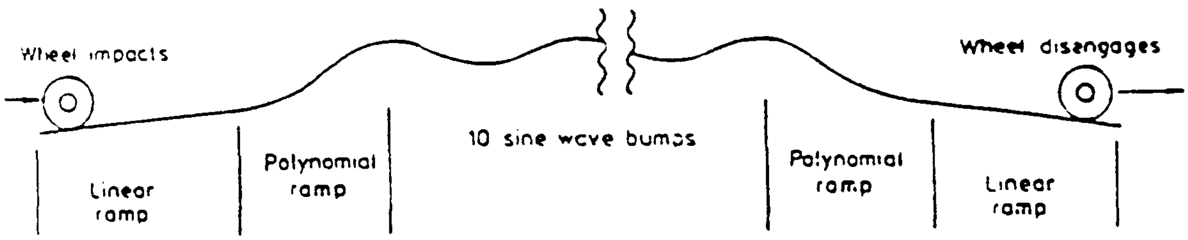
5 Testing procedure

A standard testing procedure was employed for all the six centrifuge tests reported here. After the saturation was completed the centrifuge model was transported very carefully onto the centrifuge arm. Immediately after the loading procedure was complete the strong box was fixed to make the centrifuge model level. Pre flight checks were completed at this stage. Just before starting up the centrifuge motor, the strong box was released to hang freely at the end of the arm.

The centrifuge acceleration was increased in steps of 20g,40g,60g and 80g. At each stage the pore pressures within the model were monitored using a DVM. After the testing acceleration of 80g was achieved at the centroid of the model the steady acceleration was maintained for 20 minutes before any earthquake was fired. The pore pressures were monitored again after the 20 minutes. An earthquake was fired and the data was plotted. The strength of the subsequent earthquakes was gradually increased. When the test was finished the centrifuge was showed down and stopped. The model was recovered from the pit carefully and the post test profile of the levee was measured.

6 Presentation of test data

FLY-14 suite of programs was used to digitise the data recorded using a 14 channel Racal tape recorder. The earthquake strength is expressed as a percentage of the centrifugal acceleration. The acceleration time histories are presented with the transducer number which recorded the trace. The excess pore pressures generated were presented in the units of kPa and are shown with the transducer number. Each of these traces contains 1024 data points collected in a time of 200 ms giving a data point spacing of 1.95×10^{-4} seconds. The Nyquist frequency of the data is 2.56 kHz.



Schematic diagram showing the transitional curves before and after the sinusoidal wave track

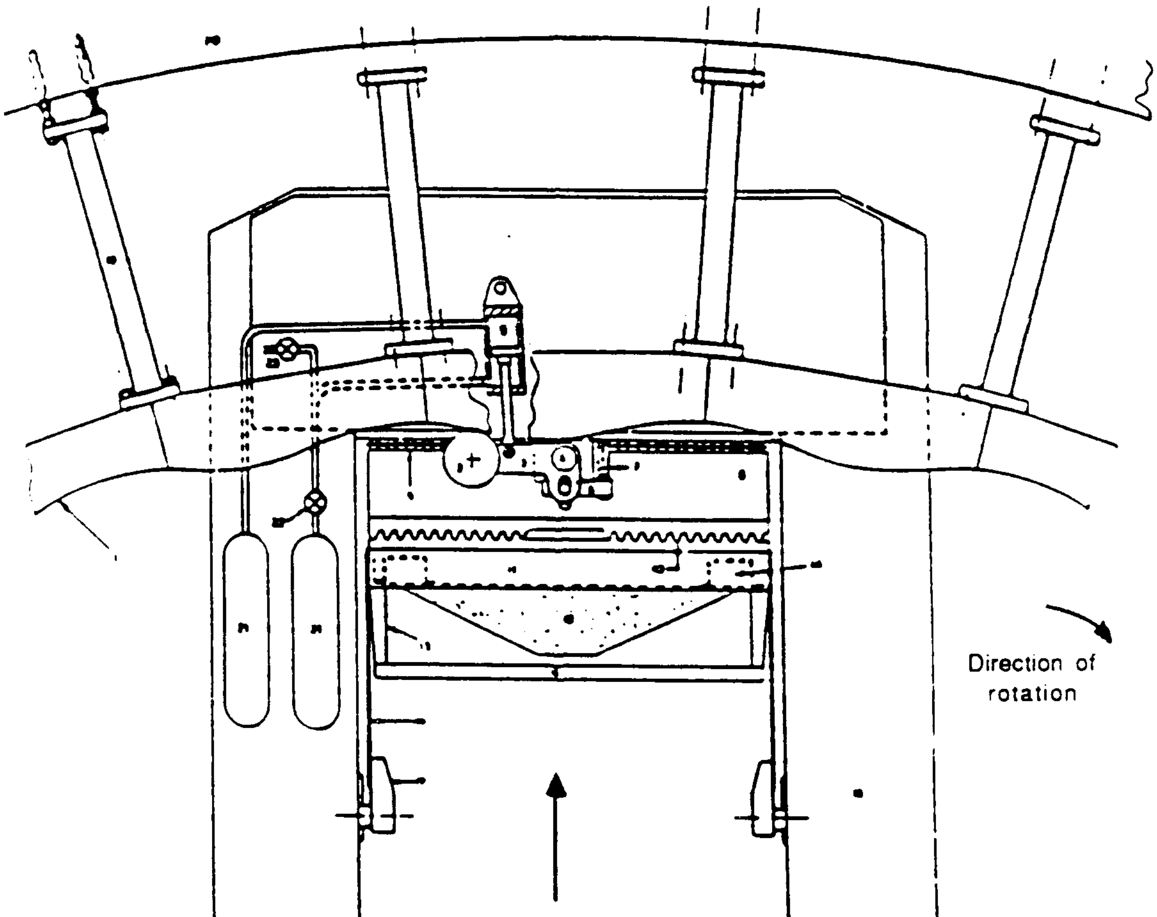


Fig. 1 Schematic view of Bumpy road shaking system with the strong box in swung up position (after Kutter, 1982)

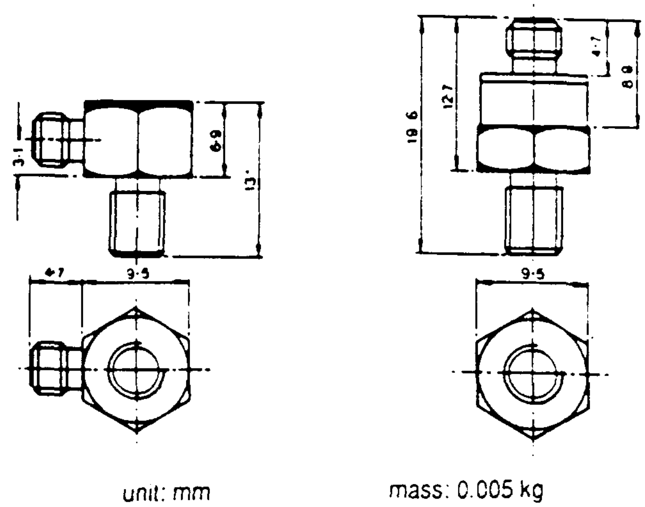


Fig.2a Typical dimensions of an accelerometer

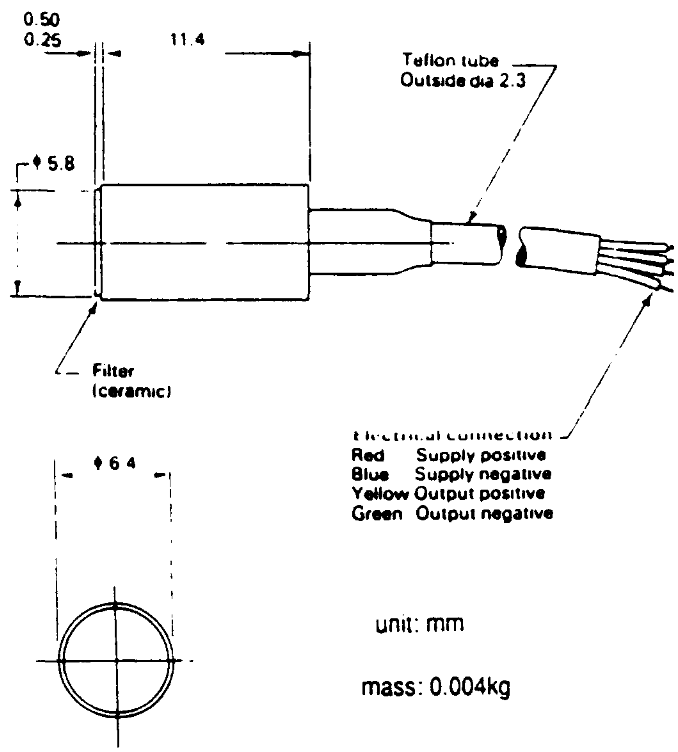


Fig.2b Typical dimensions of an pore pressure transducer

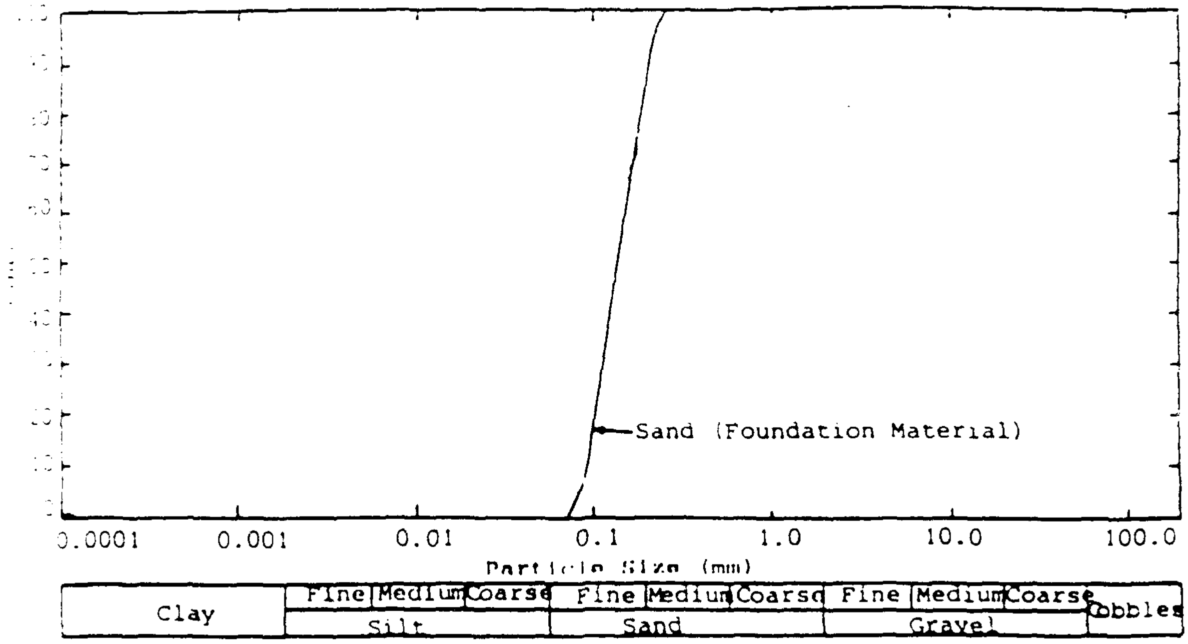


Fig.3a Grain size distribution curve for LB 52/100 sand

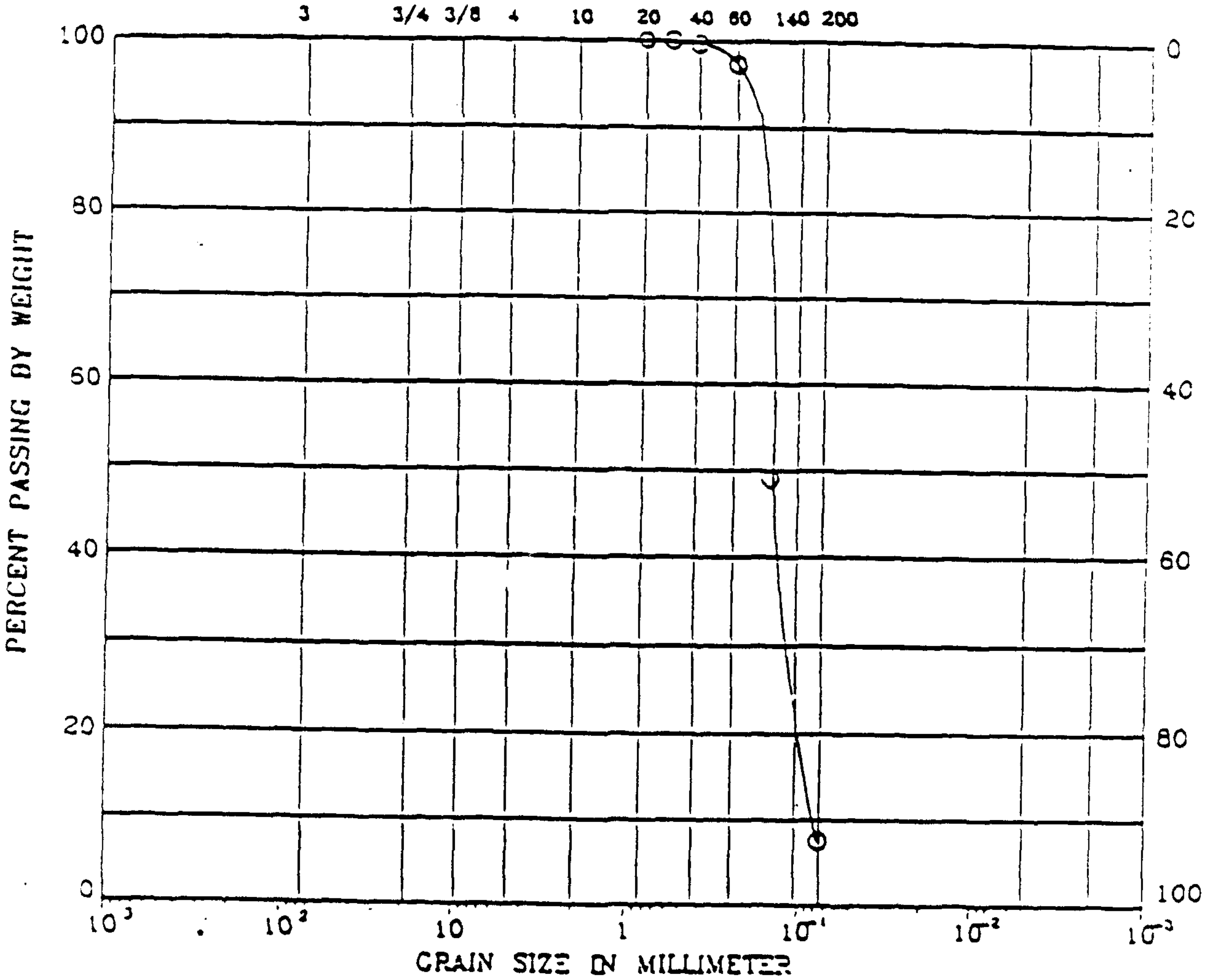


Fig.3b Grain size distribution of Nevada 120 sand

GEM - 1

7 Centrifuge test GEM-1

7.1 *Configuration of the test*

The seismic response of an embankment with a loose sand deposit on one side was investigated by conducting a dynamic centrifuge test GEM-1. The water table was kept plush with the top of the embankment in this test. In a subsequent test a draw down on the down stream side of the embankment is included and the loose sand deposit was placed on the up stream side. In this centrifuge test a new modelling technique of freezing a loose sand deposit and placing it on an array of Peltier Heat Pumps was investigated. The loose deposit is protected from densification due to any disturbances during model preparation and tranfer of centrifuge model on to the centrifuge arm.

The schematic section of the model used in this centrifuge test is shown in Fig.7.1a. This report discusses the new modelling techniques used in this test to construct a loose section of sand in a relatively dense embankment. Also, the data from this centrifuge test will be presented.

7.2 *Construction of the model*

7.2.1 *Loose section of the embankment*

The problem of preparing a loose sand model is that it is likely to be densified due to some unavoidable disturbances during the transit of the strong box from model preparation room to the centrifuge arm. During the centrifuge test GEM-1 the loose section was prepared in a 'one dimensional freezing box' with a metal base, plywood sides and a polysterene top. The Nevada 120 sand was rained into the freezing box and the instruments are placed at required positions as shown in Fig.7.1b. This loose model was then carefully saturated. Once the saturation was completed the freezing box was transfered into a deep freeze and was maintained at -20^0C. The water in the loose soil sample freezes from the base and this ice front propagates upwards. Care was taken to align the PPT's properly so that the diaphram of the transducer does not get damaged due to the anomalous expansion of water between 4^0C and 0^0C. Thermistors were used to monitor the temparature of the soil model.

7.2.2 *Peltier Devices*

The frozen loose model is then transfered onto an array of Peltier Heat Pumps. These devices are used to pump heat from the frozen soil sample to the strong box which was used as a large heat sink during this centrifuge test. The design and construction of the Peltier Heat Pumping Array (PHPA) will be discussed in a subsequent technical report.

7.2.3 Main embankment section

The dense section of the embankment was constructed around the loose frozen soil model. The PHPA devices help the loose model to sustain in a frozen state during this operation. The LB 52/100 sand was rained from a sand hopper from a predetermined height and the embankment section was gradually constructed after placing the instruments in the soil body at required levels. After the preparation of the embankment was completed a vacuum of -27.5 mm of Mercury was applied to the model. The embankment model was saturated with water under this vacuum while the PHPA devices were still on. The water table at the end of saturation was maintained plush with the crest of the embankment. The model was then transfered to the centrifuge arm keeping the PHPA devices running and maintaining the vacuum. The PHPA devices are switched off once the model was securely hung at the end of the centrifuge arm. The vacuum pressure was slowly released. When the frozen section of loose sand has completely thawed the centrifuge was started. It was assumed that, on thawing the frozen loose sand sample would retain its high void ratio if it was not subjected to any disturbances, Smith (1991).

7.3 Centrifuge test data

The centrifuge was accelerated to 80 g and a total of three earthquakes were fired such that the strength of the earthquake was gradually increased. The placement of transducers is shown in Fig.7.1b. The time histories recorded by these transducers are presented in figures 7.2 to 7.7. The accelerations are expressed as a percentage of the centrifugal acceleration and the excess pore pressures are given in kPa units.

The first earthquake had a strength of 6.3 % as measured at the base of the embankment by ACC 1552. This is shown as the bottom trace in Fig.7.2. The accelerometer situated in the crest of the embankment recorded large acceleration indicating the movement of the crest towards the loose section side of the embankment. Excess pore pressures were generated within the embankment and the traces recorded by various PPT's are shown in Figs.7.2 and 7.3.

The acceleration and excess pore pressures observed during earthquake 2 are presented in figures 7.4 and 7.5. The base acceleration is again represented by ACC 1552. Large suction pressures were observed near the surface of the embankment as indicated by PPT 6159 in Fig.7.4. The results from earthquake 3 are presented in figures 7.6 and 7.7. The profile of the embankment was measured before and after the centrifuge test. These are presented in figure 7.8.

Plate 7.1 Placement of the Peltier heat pumping devices and instruments

Plate 7.2 Construction of the dense section

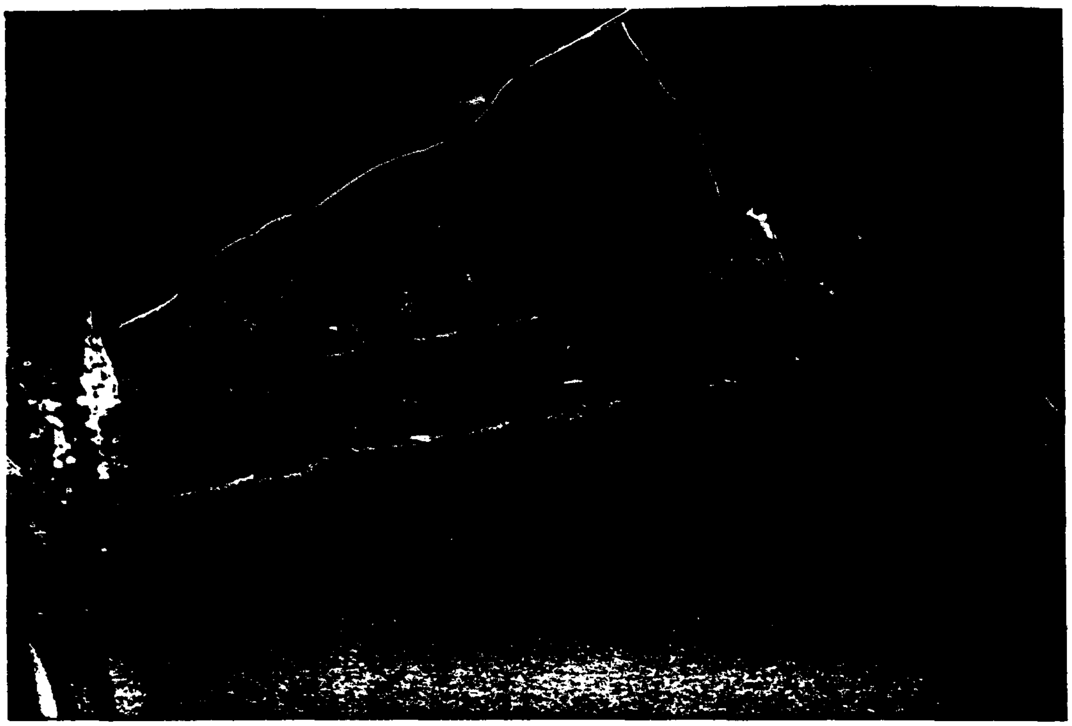
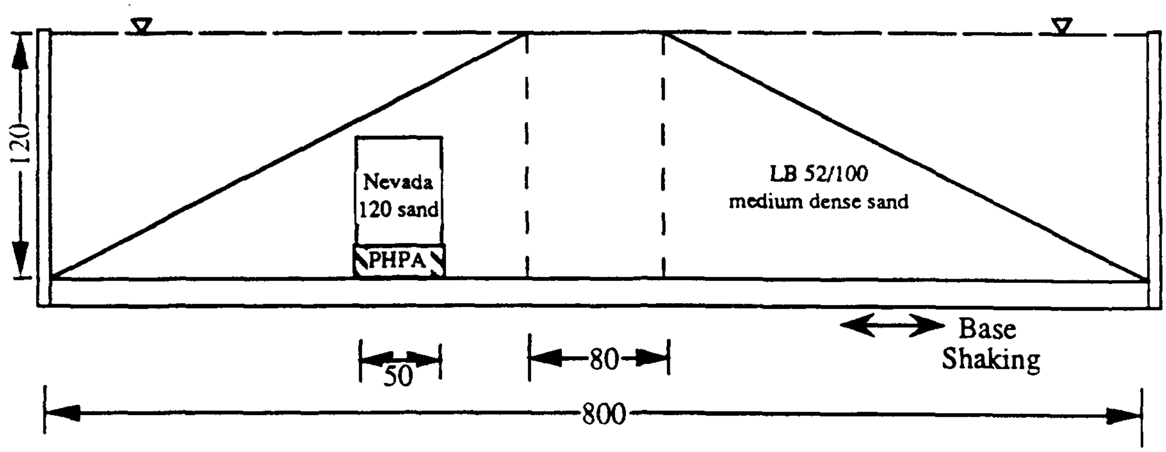


Plate 7.3 Frozen loose pocket placed on PHPA devices

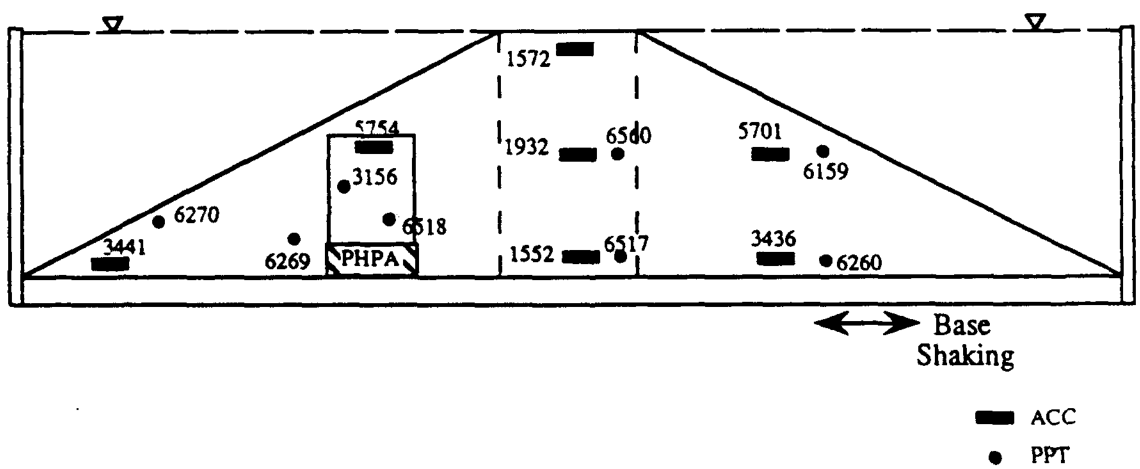
Plate 7.4 Final profile of the levee before saturation

Plate 7.5 Settlement of the crest after the earthquakes

Plate 7.6 Section showing the loose Nevada sand (observe the PPT head)

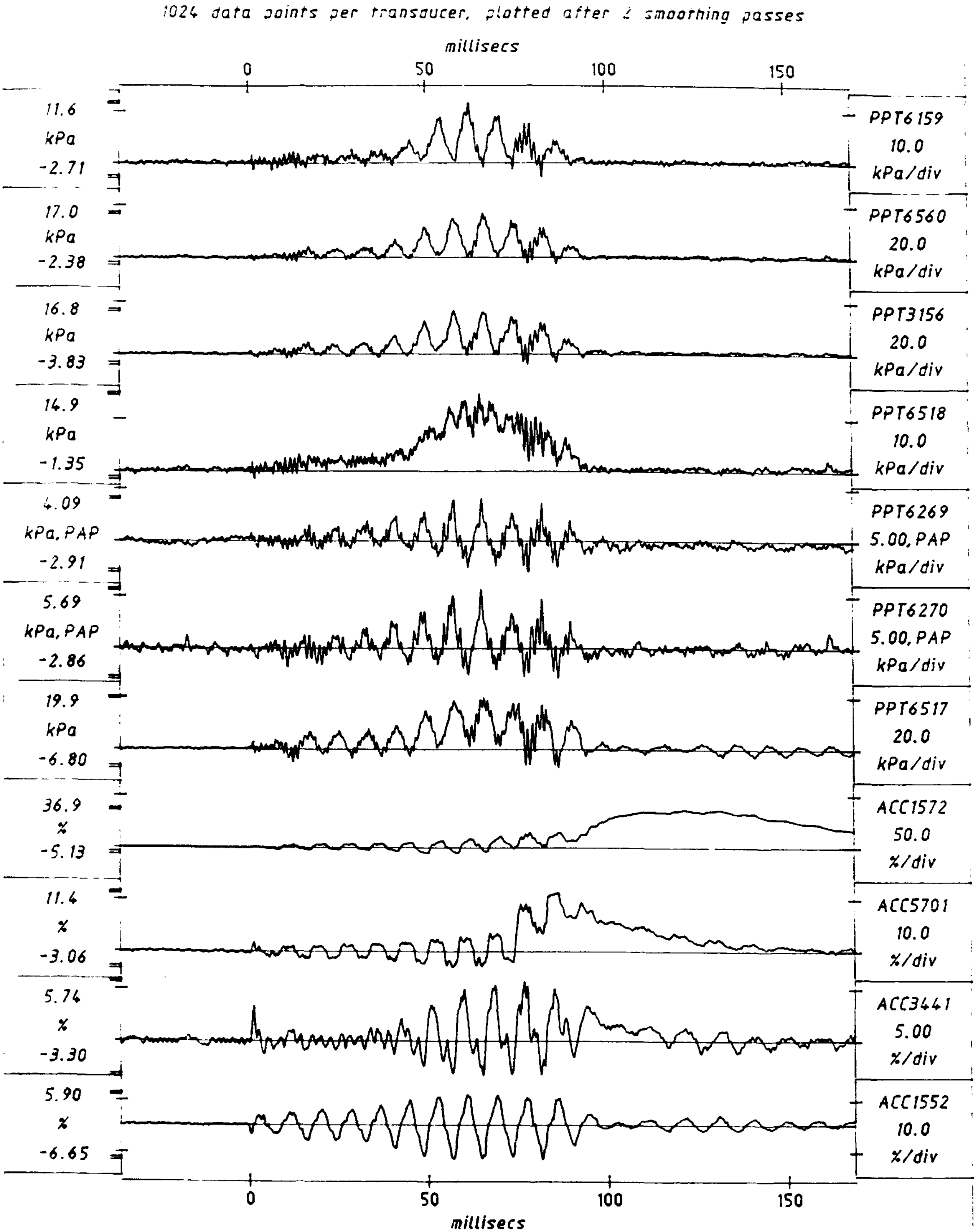


A) Schematic section of the centrifuge model GEM-1



B) Placement of transducers in centrifuge model GEM-1

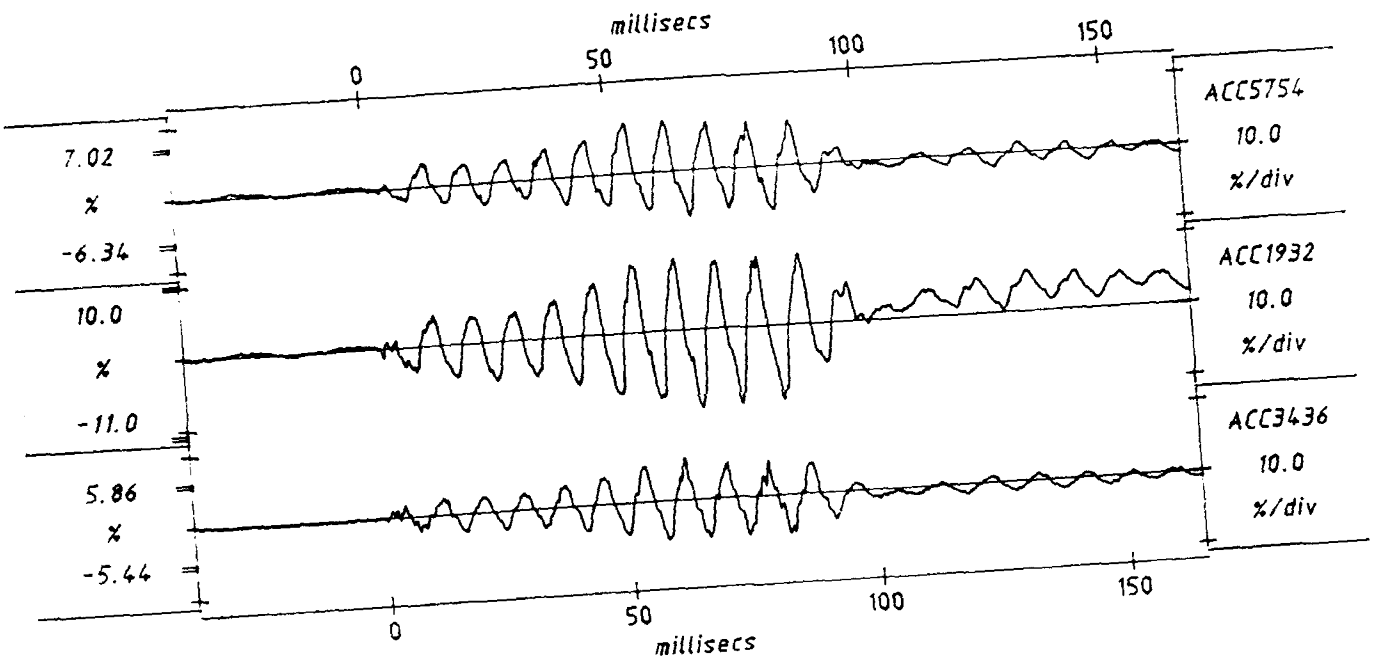
FIG. 7.1



Scales : Model

TEST GEM1 MODEL LD FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 6.28% Kp = 6.65%	FIG. NO. 7.2

1024 data points per transducer, plotted after 2 smoothing passes



Scales : Model

TEST GEM1 MODEL LD FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 5.65% Kp = 5.86%	FIG. NO. 7.3

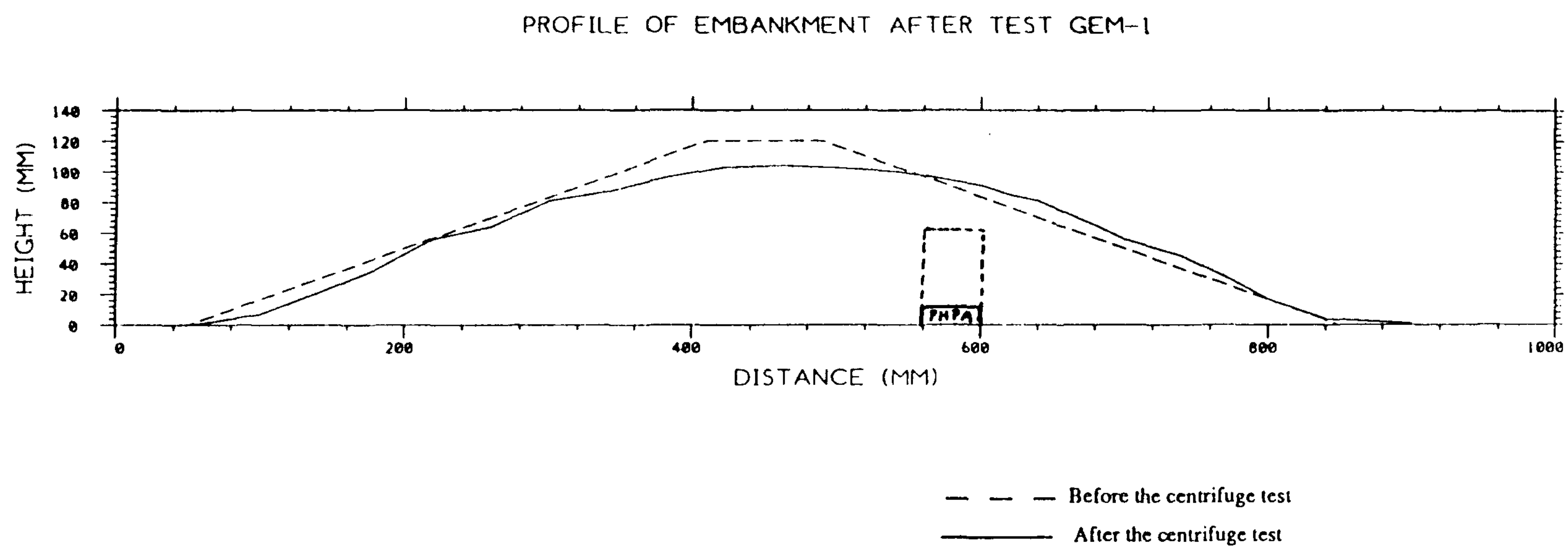
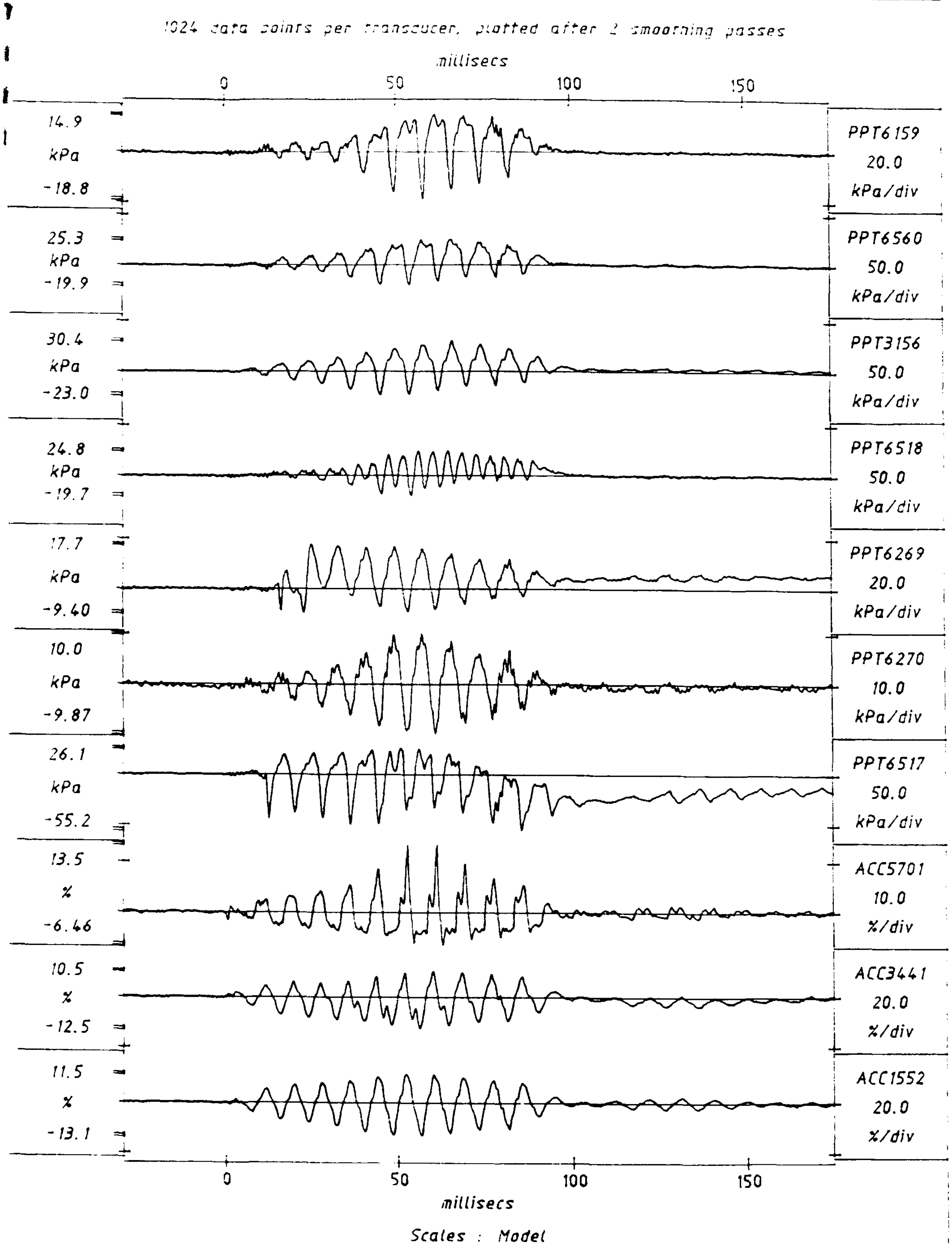


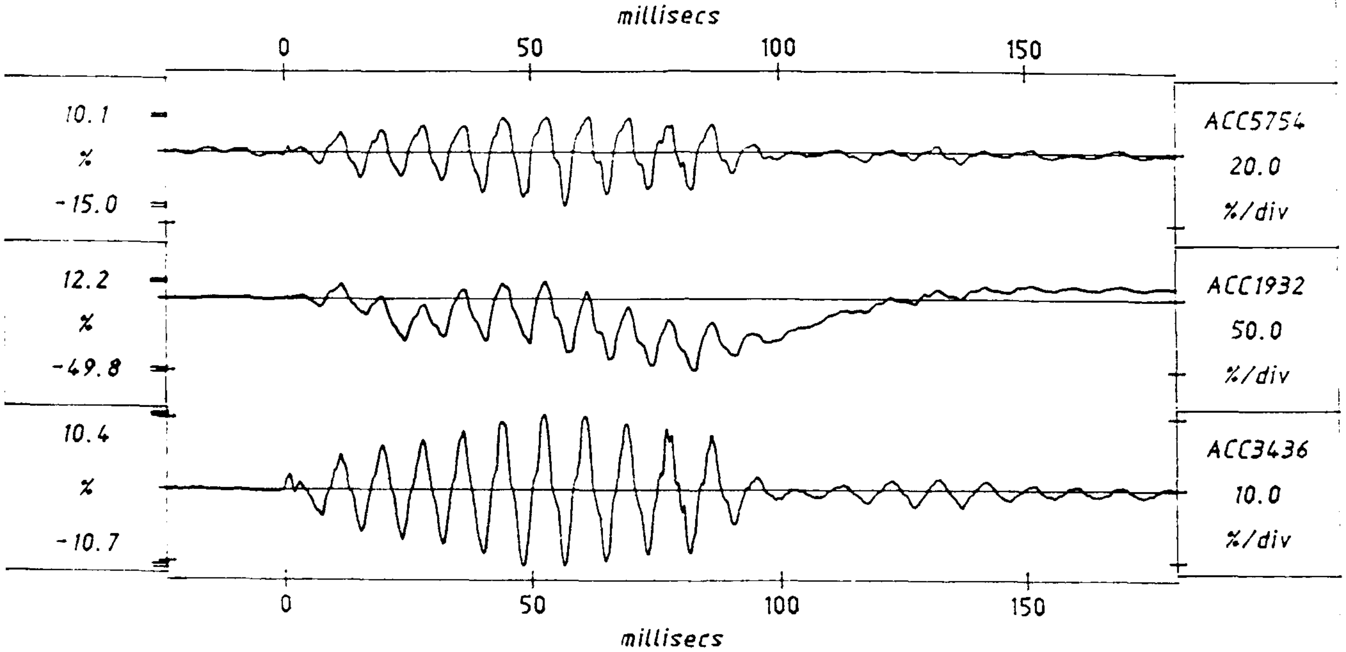
Fig.7.8 Section of the embankment before and after the centrifuge test GEM-1

GEM - 2



TEST GEM1 MODEL LD FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 12.3% Kp = 13.1%	FIG. NO. 7.6

1024 data points per transducer, plotted after 2 smoothing passes



Scales : Model

TEST GEM1 MODEL LD FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 10.5% Kp = 10.7%	FIG. NO. 7.7

8 Centrifuge test GEM-2

8.1 Configuration of the test

The seismic response of an embankment with a loose sand deposit on the upstream side was investigated by conducting a dynamic centrifuge test GEM-2. A draw down in the water level on the down stream side was achieved after the centrifuge has accelerated to '80g' and the model has stabilized. A thin latex rubber barrier was used to prevent the seepage of water through the centrifuge model (see Fig.8.1a). The water table was kept plush with the top of the embankment at the start of the test. In this centrifuge test the earlier modelling technique of freezing a loose sand deposit and placing it on an array of Peltier Heat Pumps was used as described earlier. The loose deposit is protected from densification due to any disturbances during model preparation and tranfer of centrifuge model on to the centrifuge arm.

The schematic section of the model used in this centrifuge test is shown in Fig.8.1a. This report discusses the new modelling techniques used in this test to construct a loose section of sand in a relatively dense embankment. Also, the data from this centrifuge test will be presented.

8.2 Construction of the model

8.2.1 Loose section of the embankment

The problem of preparing a loose sand model is that it is likely to be densified due to some unavoidable disturbances during the transit of the strong box from model preparation room to the centrifuge arm. During the centrifuge test GEM-2 the loose section was prepared in a 'one dimensional freezing box' with a metal base, plywood sides and a polysterene top. The Nevada 120 sand was rained into the freezing box and the instruments are placed at required positions as shown in Fig.8.1b. This loose model was then carefully saturated. Once the saturation was completed the freezing box was transfered into a deep freeze and was maintained at -20^0C. The water in the loose soil sample freezes from the base and this ice front propagates upwards. Care was taken to align the PPT's properly so that the diaphram of the transducer does not get damaged due to the anomalous expansion of water between 4^0C and 0^0C. Thermistors were used to monitor the temparature of the soil model.

8.2.2 Peltier Devices

The frozen loose model is then transfered onto an array of Peltier Heat Pumps.

These devices are used to pump heat from the frozen soil sample to the strong box which was used as a large heat sink during this centrifuge test. The design and construction of the Peltier Heat Pumping Array (PHPA) will be discussed in a subsequent technical report.

8.2.3 Seepage barrier

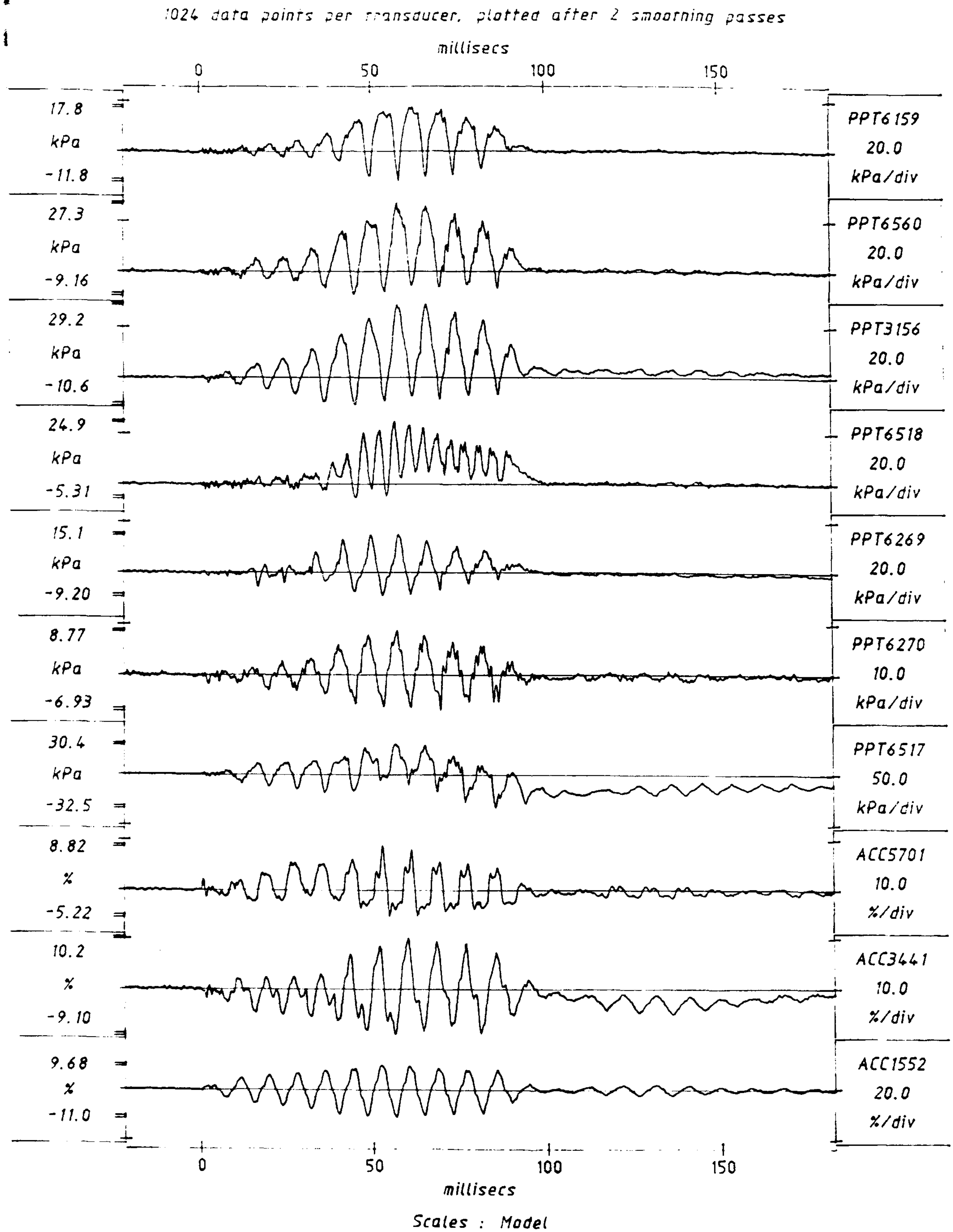
A thin latex rubber sheet was placed at the centre of the model of the model as shown schematically in Fig.8.1a. The latex sheet eas sealed at its ends using silicone rubber to prevent any leakage from the ends. Similar sealing was provided along the base of the latex sheet. The stiffness of the seepage barrier in the direction of the model earthquake was assumed to be negligible.

8.2.4 Main embankment section

The dense section of the embankment was constructed around the loose frozen soil model which was situated on the upstream side of the embankment. The PHPA devices help the loose model to sustain in a frozen state during this operation. The LB 52/100 sand was rained from a sand hopper from a predetermined height and the embankment section was gradually constructed after placing the instruments in the soil body at required levels. After the preparation of the embankment was completed a vacuum of -27.5 mm of Mercury was applied to the model. The embankment model was saturated with water under this vacuum while the PHPA devices were still on. The water table at the end of saturation was maintained plush with the crest of the embankment. The model was then transfered to the centrifuge arm keeping the PHPA devices running and maintaining the vacuum. The PHPA devices are switched off once the model was securely hung at the end of the centrifuge arm. The vacuum pressure was slowly released. When the frozen section of loose sand has completely thawed the centrifuge was started. It was assumed that, on thawing the frozen loose sand sample would retain its high void ratio if it was not subjected to any disturbances, Smith (1991).

8.3 Centrifuge test data

The centrifuge was accelerated to 80 g and a total of three earthquakes were fired such that the strength of the earthquake was gradually increased. The placement of transducers is shown in Fig.8.1b. The time histories recorded by these transducers are presented in figures 8.2 to 8.5. The accelerations are expressed as a percentage of the centrifugal acceleration and the excess pore pressures are given in kPa units.



TEST GEM1
MODEL LD
FLIGHT 1

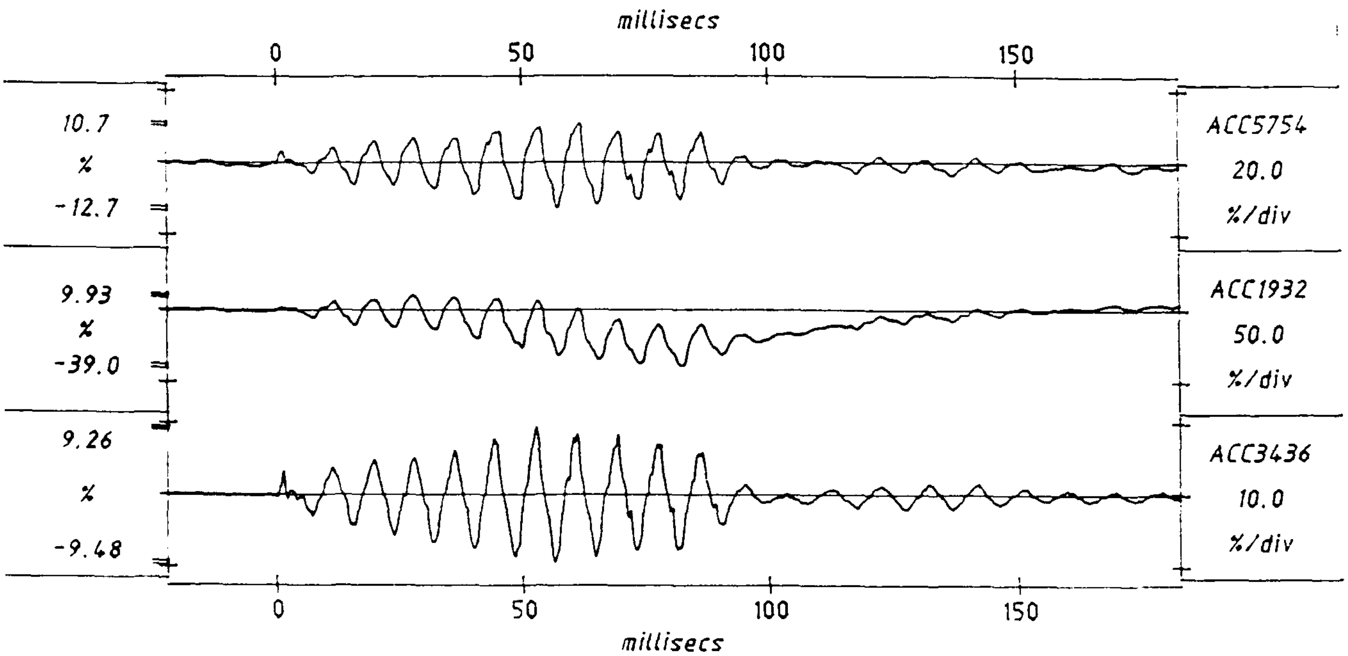
EQ2

SHORT-TERM
TIME RECORDS

G = 80.0g
Km = 10.4%
Kp = 11.0%

FIG. NO.
7.4

1024 data points per transducer, plotted after 2 smoothing passes



Scales : Model

TEST GEM1 MODEL LD FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 9.37% Kp = 9.48%	FIG. NO. 7.5

The centrifuge is spun up to the required centrifugal acceleration of '80 g'. After the centrifugal model has obtained a steady state configuration. the drains on the down stream side of the embankment were released by operating a pnuematic valve. The pore pressure transducers on the upstream side and the down stream side of the embankment were monitored. On achieving the required draw down of water level on the down stream side the pnuematic air valve is operated again and the drains were closed. The centrifuge model was allowed to achieve a steady state and two earthquakes were fired using the Bumpy Road excitation system.

The first earthquake had a strength of 23.1 % as measured at the base of the embankment by ACC 1552. This is shown as the bottom trace in Fig.8.2. The accelerometer situated in the crest of the embankment recorded large acceleration indicating the movement of the crest towards the loose section side of the embankment. Excess pore pressures were generated within the embankment and the traces recorded by various PPT's are shown in Figs.8.2 and 8.3.

The acceleration and excess pore pressures observed during earthquake 2 are presented in figures 8.4 and 8.5. The base acceleration is again represented by ACC 1552 and was 25.6 % during this earthquake. Large suction pressures were observed near the surface of the embankment as indicated by PPT 6159 in Fig.8.4. The profile of the embankment was measured before and after the centrifuge test. These are presented in figure 8.6.

Plate 8.1 Seepage barrier in centrifuge test GEM-2

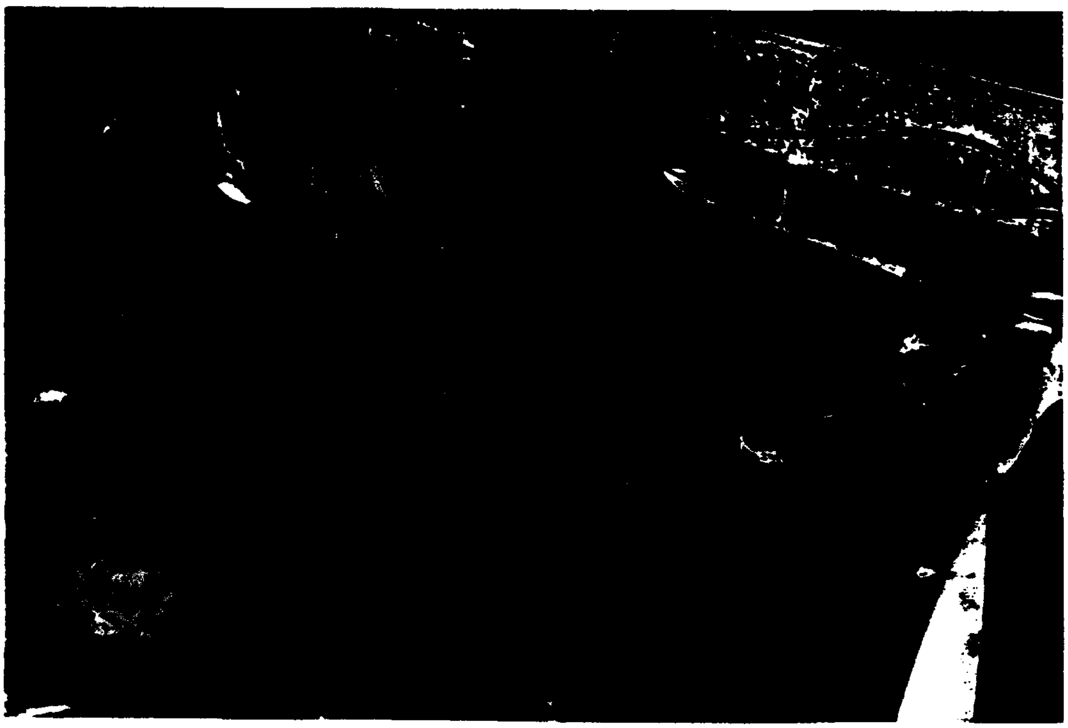
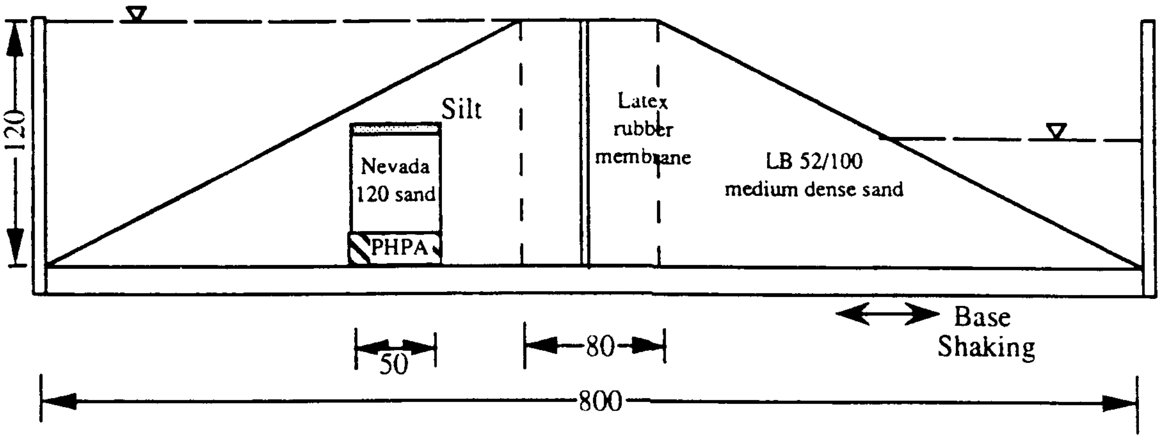
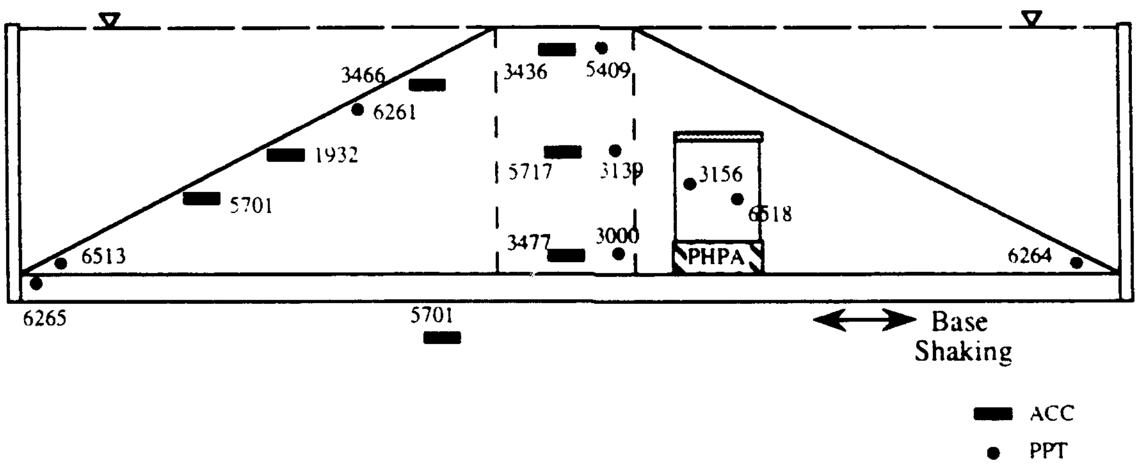


Plate 8.2 Settlement after the earthquakes in centrifuge test GEM-2

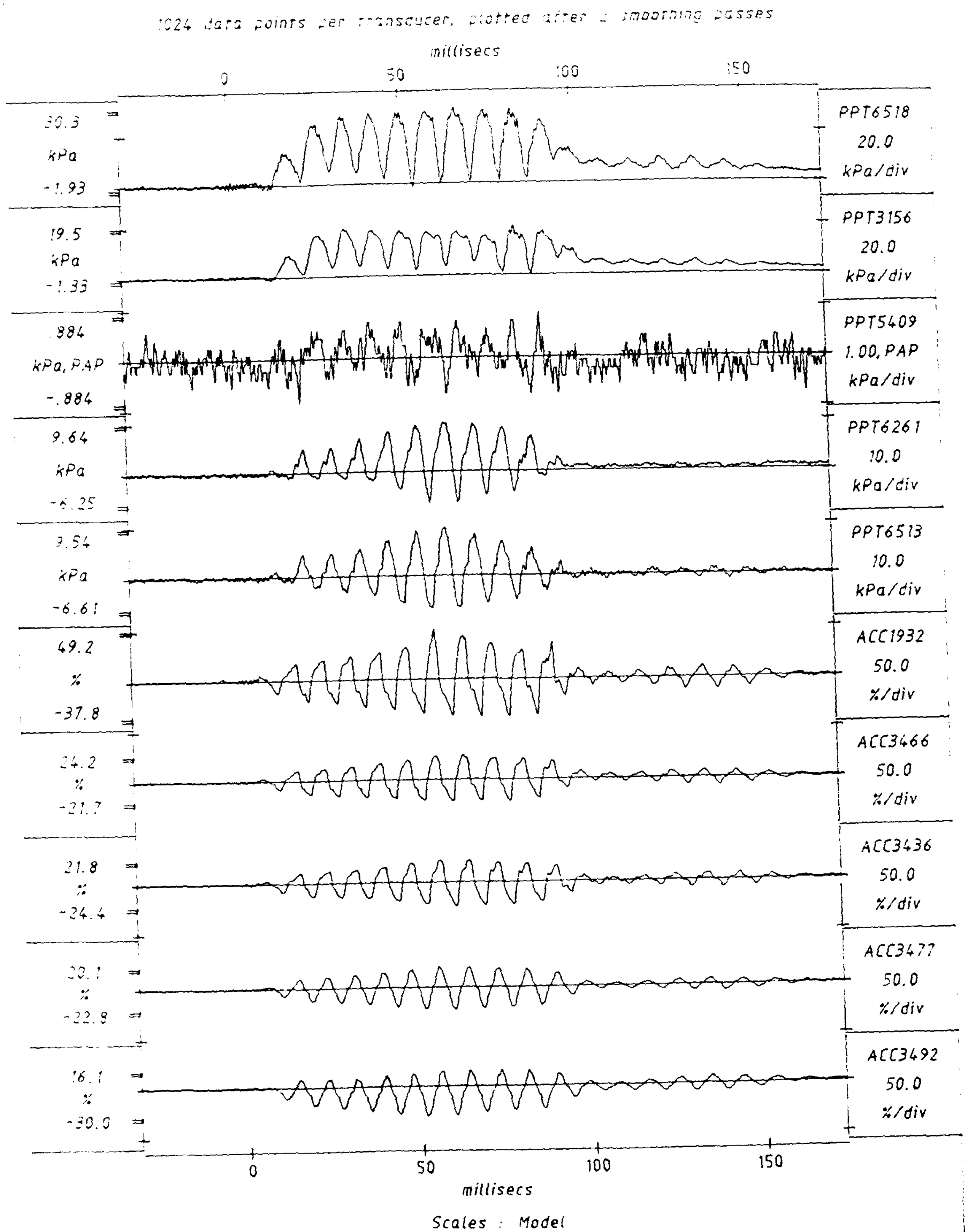


A) Schematic section of the centrifuge model GEM-2



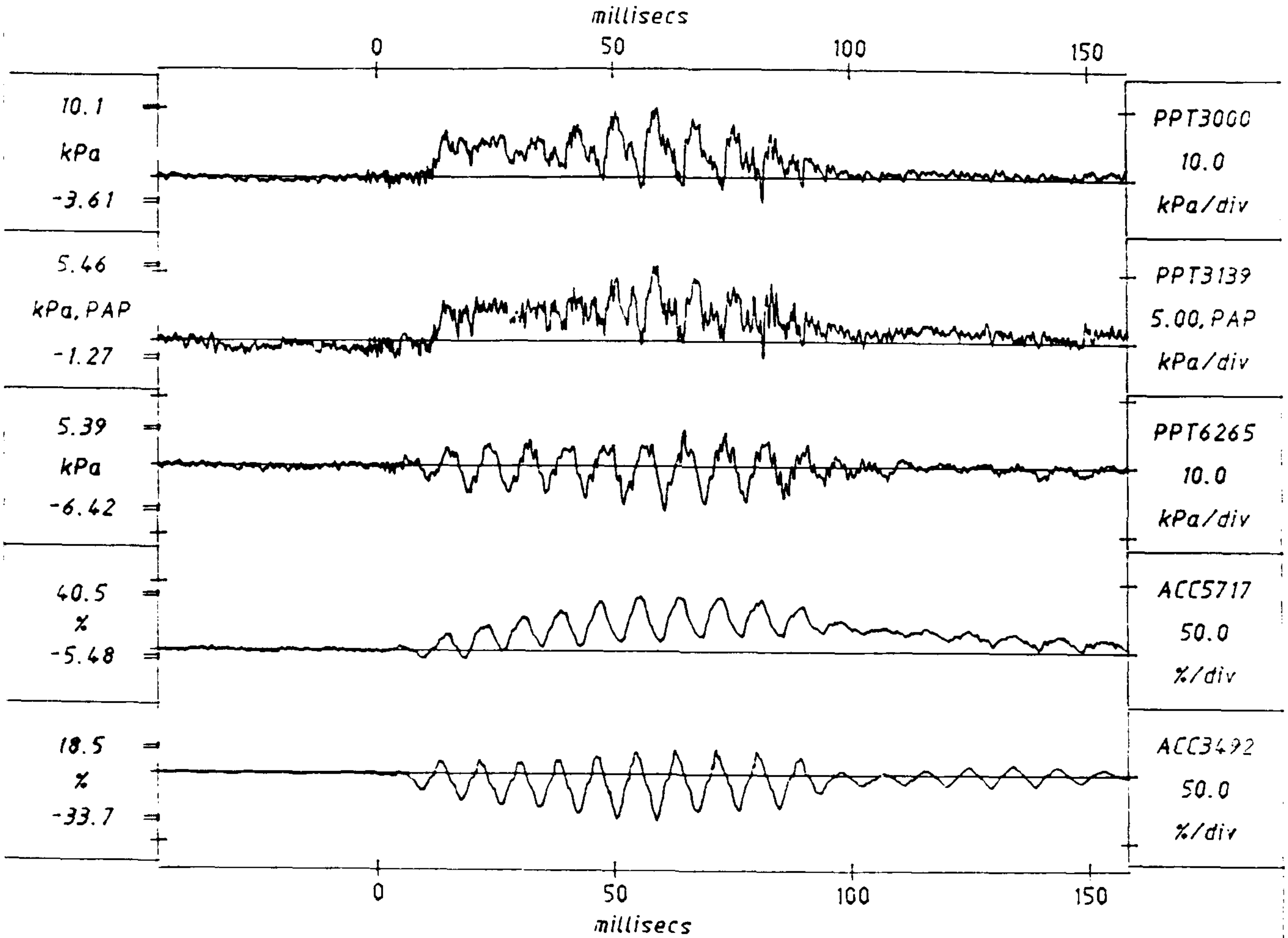
B) Placement of transducers in centrifuge model GEM-2

FIG 8.1



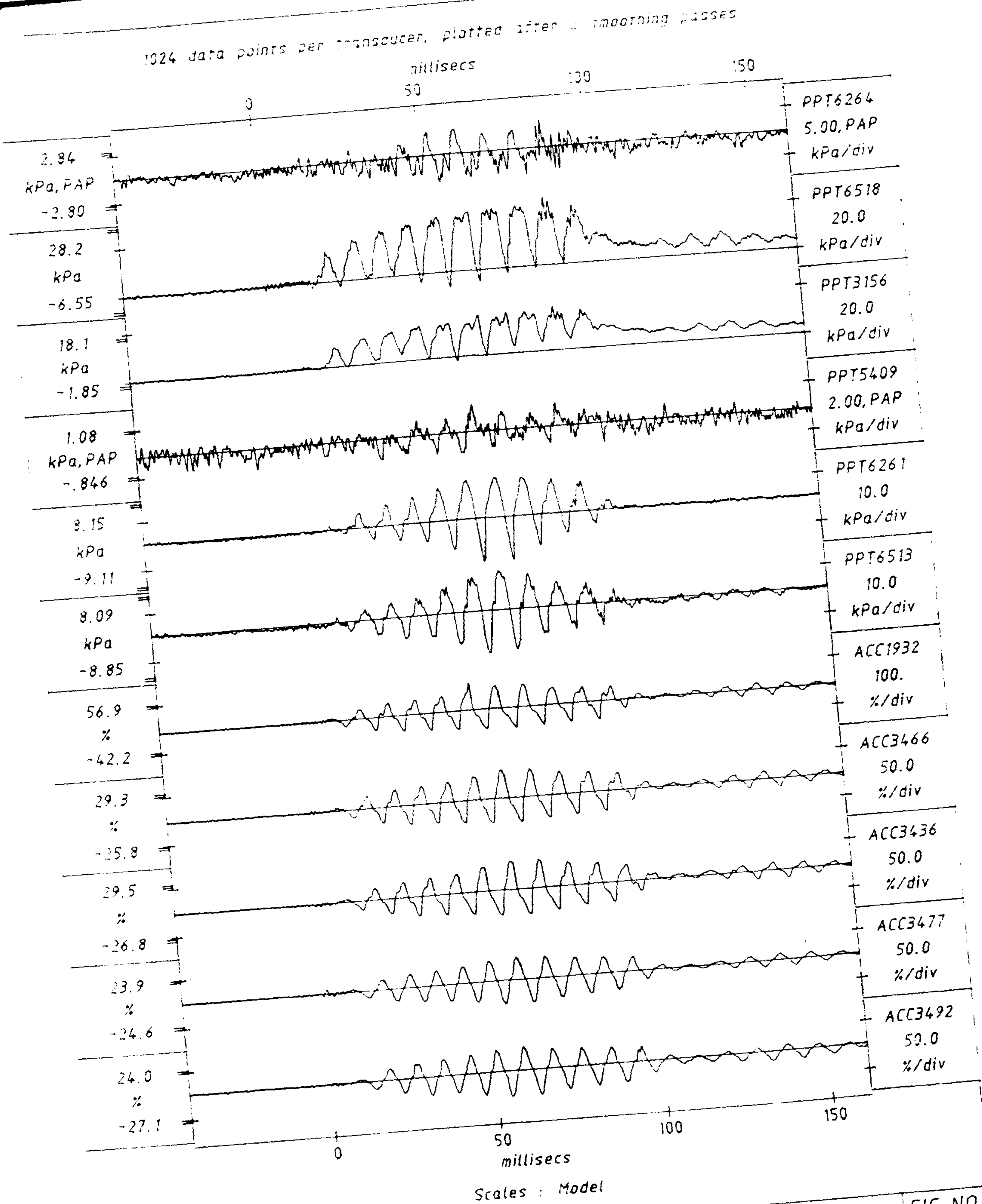
TEST GEM-2 MODEL LDB FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 23.1% Kp = 30.0%	FIG. NO. 8.2

1024 data points per transducer, plotted after 1 smoothing pass



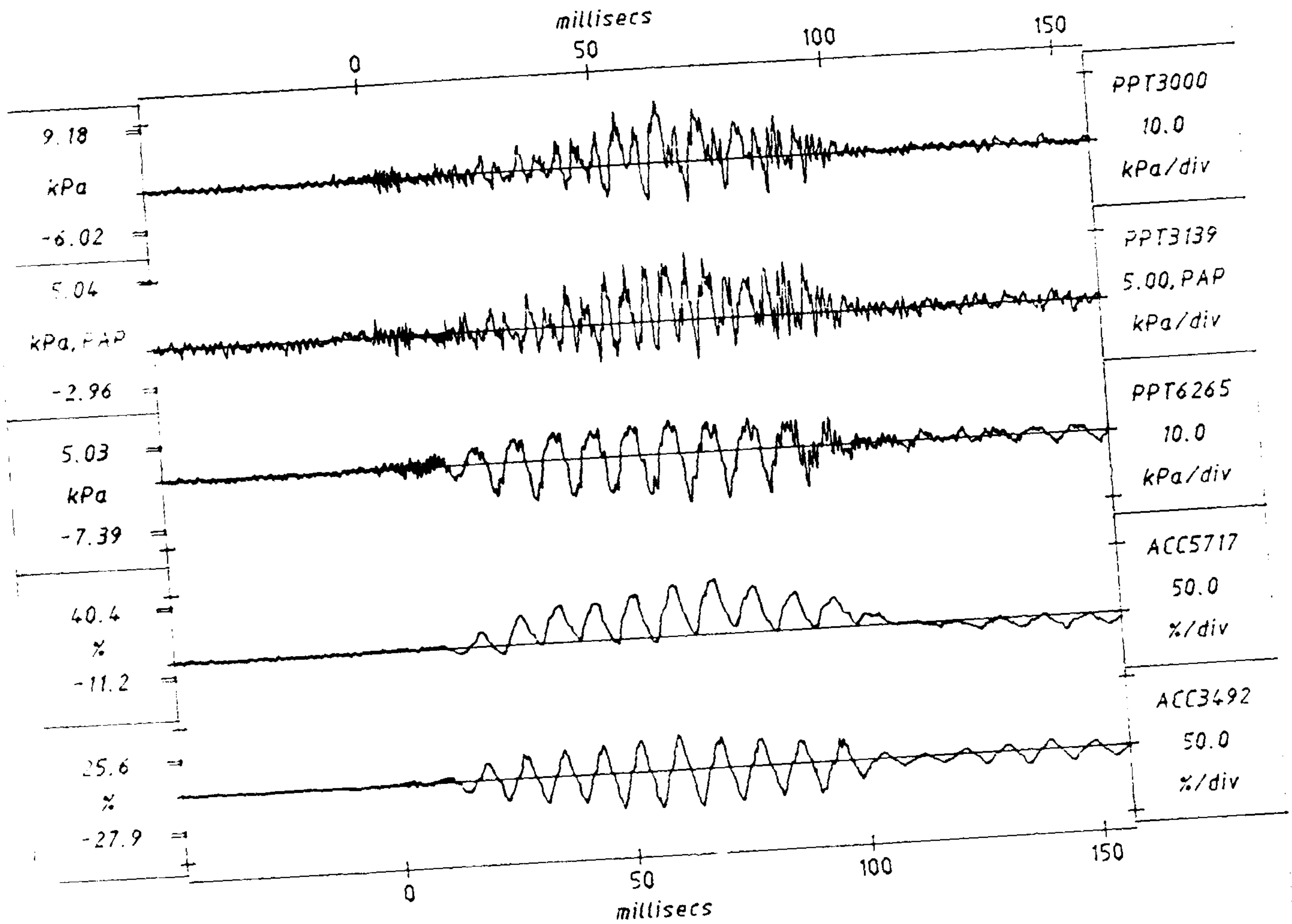
Scales : Model

TEST GFM-2 MODEL LDB FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 26.1% Kp = 33.7%	FIG. NO. 8.3



TEST GEM-2 MODEL LDB FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 25.6% Kp = 27.1%	FIG. NO. 8.4

1024 data points per transducer, plotted after 1 smoothing pass



Scales : Model

TEST GEM-2 MODEL LDB FLIGHT :	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 26.7% Kp = 27.9%	FIG. NO. 8.5

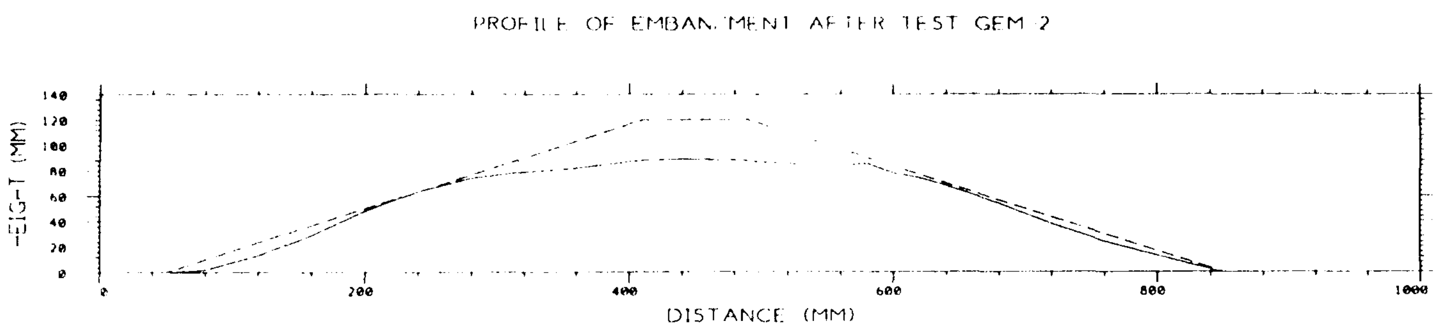


Fig.8.6 Section of the embankment before and after the centrifuge test GEM-2

9 Discussion on centrifuge tests GEM-1 and GEM-2

Based on the results from the centrifuge tests GEM-1 and GEM-2 it was observed that the PHPA devices were able to transfer the heat from the frozen loose pocket of sand to the heat sink (strong box). As a result the loose sand section was not disturbed during the model preparation as well as transportation on to the centrifuge arm. For the freezing technique to be employed it is obvious that water must be used as pore fluid. However if pore fluid is water the excess pore pressures generated within the soil body dissipate rapidly. For the correct modelling of dynamic time scaling and consolidation processes the model pore fluid must be 'N' times more viscous than water (The permeability being same in the model and the prototype while the model is only 1/N of the size of the prototype). Silicone oil whose viscosity is 80 cS is used as pore fluid in a 80g test to satisfy the scaling laws.

Four centrifuge tests were planned with silicone oil as the pore fluid. It was proposed to simulate the trapping of excess pore pressures in the loose pockets of sand due to the presence of impermeable strata around the pocket. Soft Lasagne sheets were used as the impermeable layer. The permeability of the Lasagne layer was determined under 1g conditions using a variable head permeometer. These experiments have yielded a permeability of $k = 4.19 \times 10^{-7}$ m/s.

10 Model control tests

Two model tests were conducted under 1g conditions to investigate the various methods of placing an impermeable layer of Lasagne in the sand embankment. The models were constructed exactly to the same specification as the centrifuge test models but without the placement of transducers. The typical section constructed is shown in Figs.10.1 a and b. Two thin dural plates were used as former plates for the loose section of sand. The dural plates were lubricated with water based silicone grease to minimise the disturbance to the model when they are retracted after the end of the first phase. LB 52/100 sand was rained at a predetermined rate through a sand hopper. After the construction of the first phase shown in Fig.10.1a was completed the model was vacuum levelled to the desired profile. A suction pressure of -30 cm of mercury was applied and model was thoroughly deaired. Silicone oil of 80 cS viscosity was admitted carefully at the base of the model at a very slow rate to avoid piping and boiling of sand. When the model is completely saturated to the phase I level the suction is gradually released. The dural plates were retracted carefully and the construction of phase II of the model was carried out by raining the LB 52, 100 sand as described earlier. On completion of the construction of the levee, the model was vacuum levelled to the desired profile. Again a suction of -30 cm of mercury was applied and silicone oil was applied and silicone oil was allowed at the base of the model until the model was completely saturated and the oil sea has reached the final desired level.

The model was then allowed to stand for at least 12 hours on the laboratory floor after which it was carefully transported to the centrifuge chamber and was loaded on to the arm of the centrifuge. In the case of centrifuge tests GEM 3 to 6 the suction pressure was gradually released and the instruments were connected to the data slip rings via junction box. The centrifuge was spun up after pre flight checks as described earlier. However, in the case of control tests the model was then unloaded from the centrifuge arm and brought back to the lab floor and the suction pressure was gradually released. The profile of the levee was measured and the settlement was estimated. For the dummy tests, the observed settlement was 0.2 mm at the crest of the levee and no slipping of slope occured.

Based on these control tests it was decided that the procedure of loading a model embankment with loose pocket of sand while maintaining the suction pressure was satisfactory.

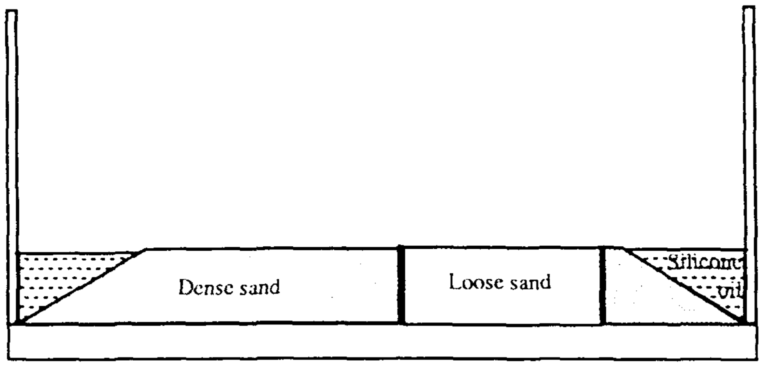


Fig.10.1 a) Phase I construction

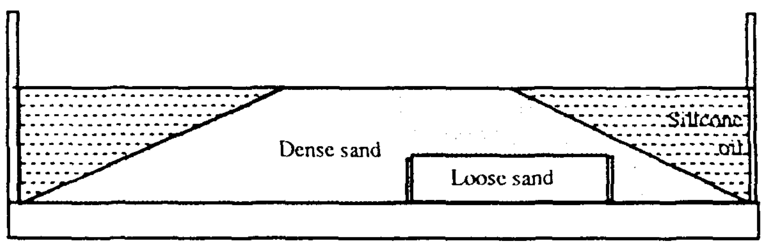


Fig.10.1 b) Phase II construction

$\boxed{\text{GEM - 3}}$

11 Centrifuge test GEM-3

11.1 Configuration of the test

A schematic section of the centrifuge model GEM-3 is presented in Fig.11.1a. The location of the transducers is indicated in Fig.11.1b. In this test the loose pocket had a thickness of 30 mm and was 175 mm long. The loose section was placed along the width of the strong box and was 480 mm wide. The silicone oil with a viscosity of 80 cS was used as pore fluid and the level of the oil sea was kept plush with the crest of the levee.

11.2 Construction of the model

The dense section to the left and right of the loose pocket of sand shown in Fig.11.1a was constructed by raining of LB 52/100 sand through a sand hopper. Former plates were fixed in position using paper wedges. Latex rubber sheets were placed on the sides of the loose pockets to prevent the dissipation of excess pore pressure. At the end of phase I of construction described in section 4.0 thin Lasagne sheets which were softened by saturation were placed on the upper surface of the loose pocket of sand (see Fig.11.1a). Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was completed.

11.3 Test data

Four earthquakes were fired on this model. The box acceleration was recorded by ACC 3436. The strength of the earthquake was increased from 17.1 % in the first earthquake to 21.2 % in the fourth earthquake. Large excess pore pressures were generated within the model levee and are recorded by various PPT's indicated in Fig.11.1b. The centrifuge test data is presented in Figs.11.2 to 11.9. After the centrifuge test the final profile of the levee was measured and post test investigations were conducted. The final profile of the levee after the test is presented in Fig.11.10.

Plate 11.1 Placement of instruments and former plates in test GEM-3

Plate 11.2 Phase I construction

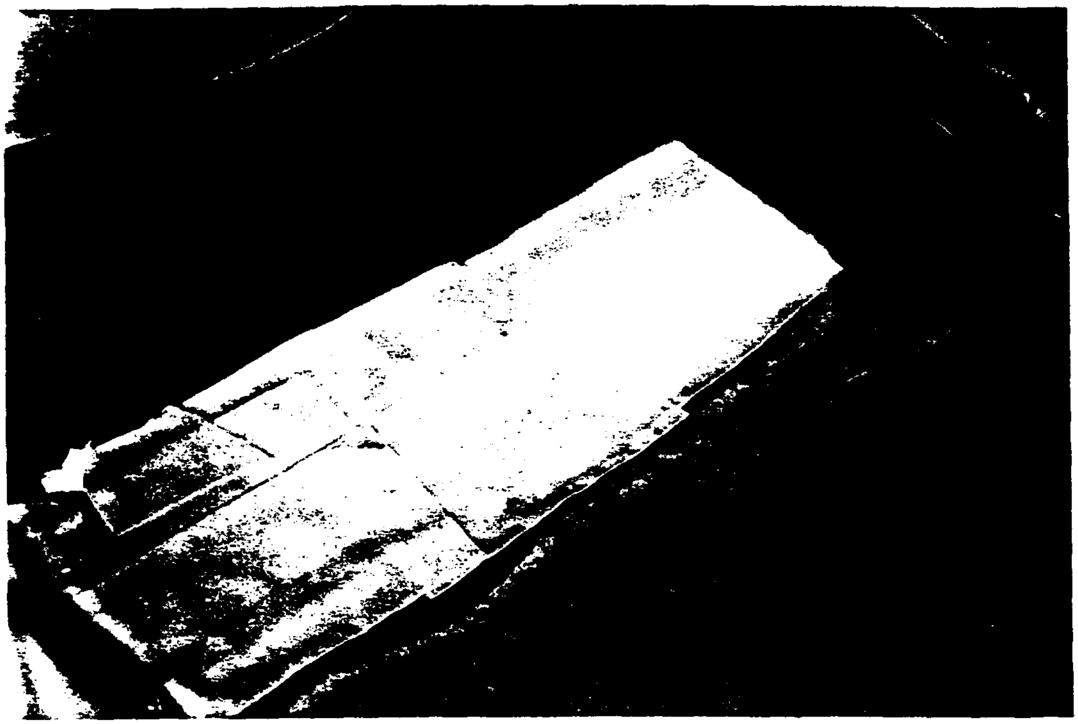
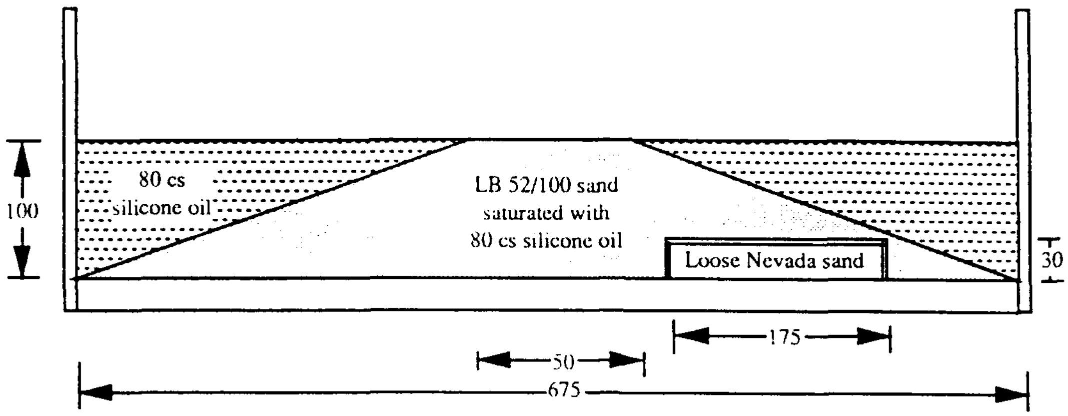


Plate 11.3 Impermeable Lasagne sheets on the top of loose pocket

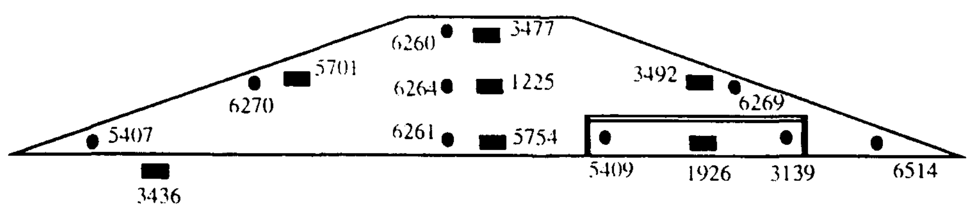
Plate 11.4 Concoidal slip surface observed during centrifuge test GEM-3

Plate 11.5 Slip surface observed from the crest towards upstream side

Plate 11.6 Floating of accelerometer due to liquefaction in concoidal slip

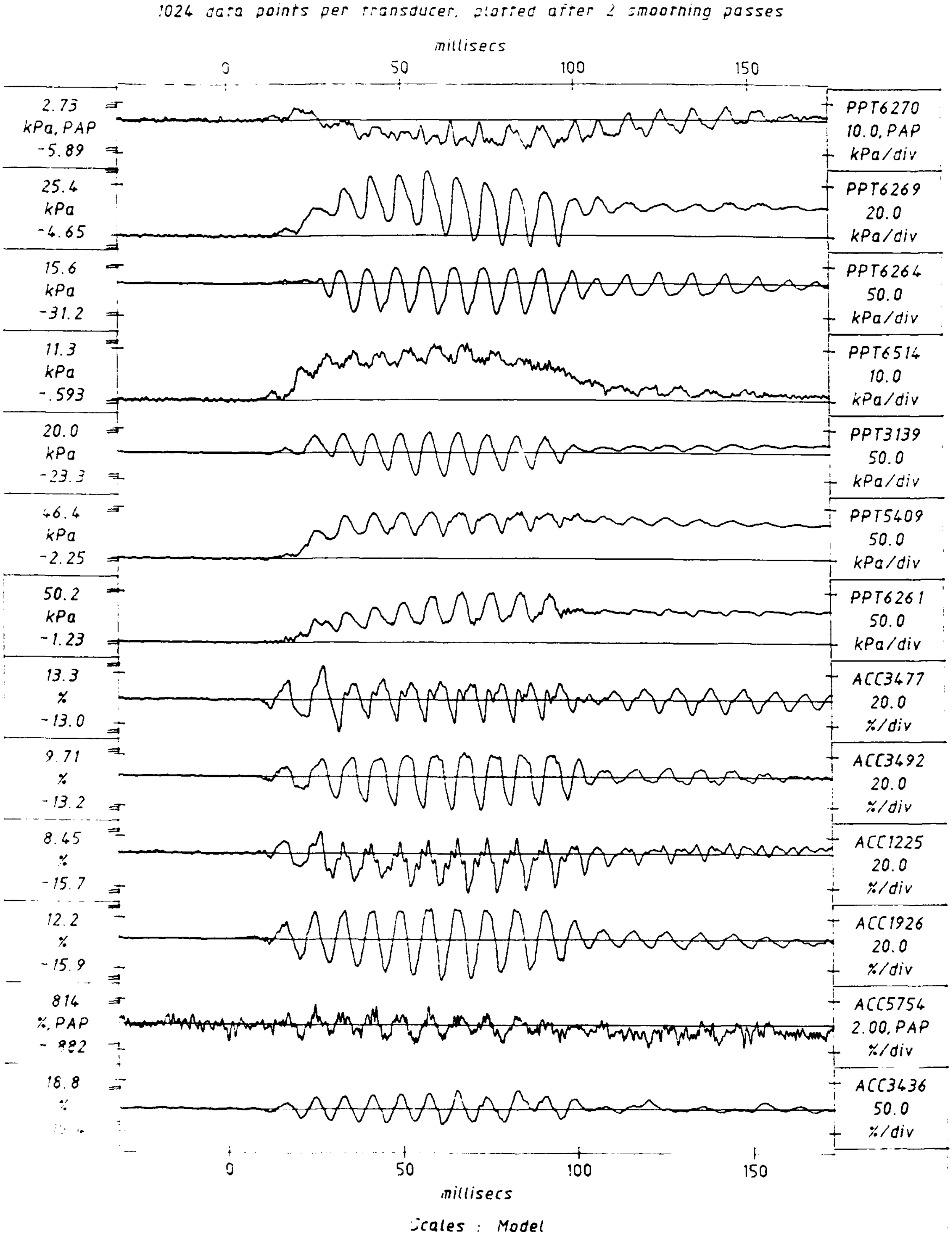


A) Schematic section of centrifuge model GEM-3



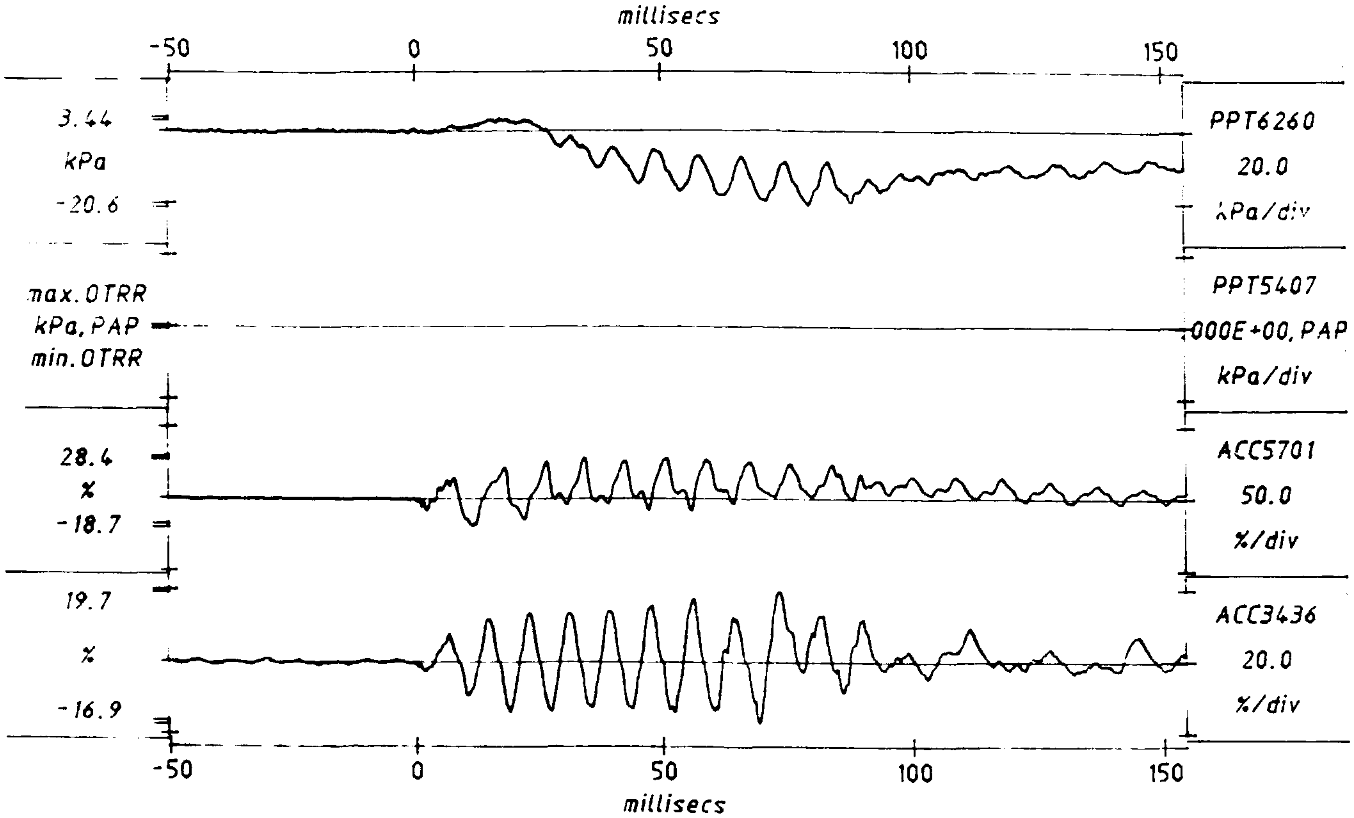
B) Placement of transducers in centrifuge test GEM-3

FIG. 11.1



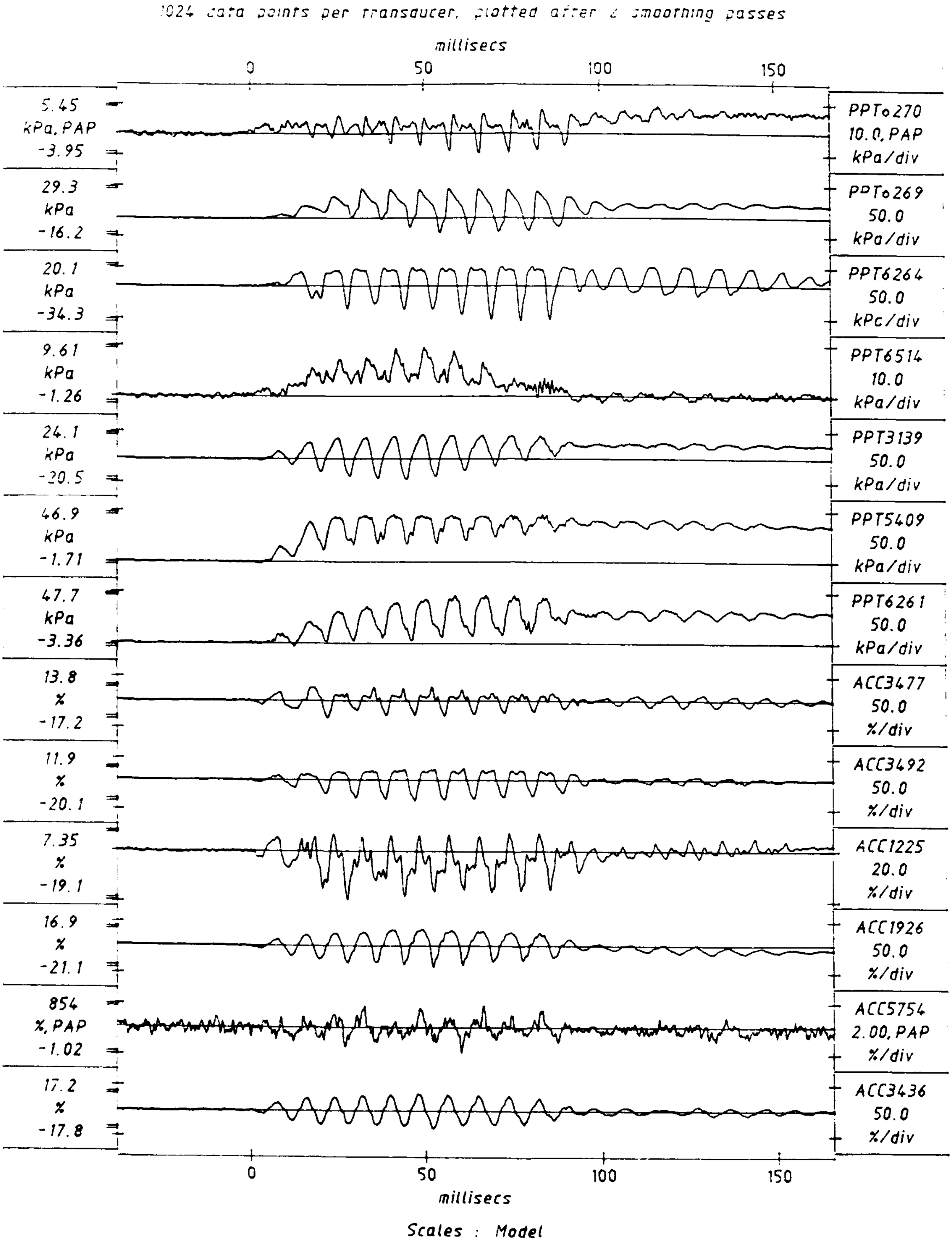
TEST GEM-3 MODEL LDO FLIGHT 1	EQ 1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 17.1% Kp = 18.8%	FIG. NO. 11.2

1024 data points per transducer, plotted after 2 smoothing passes



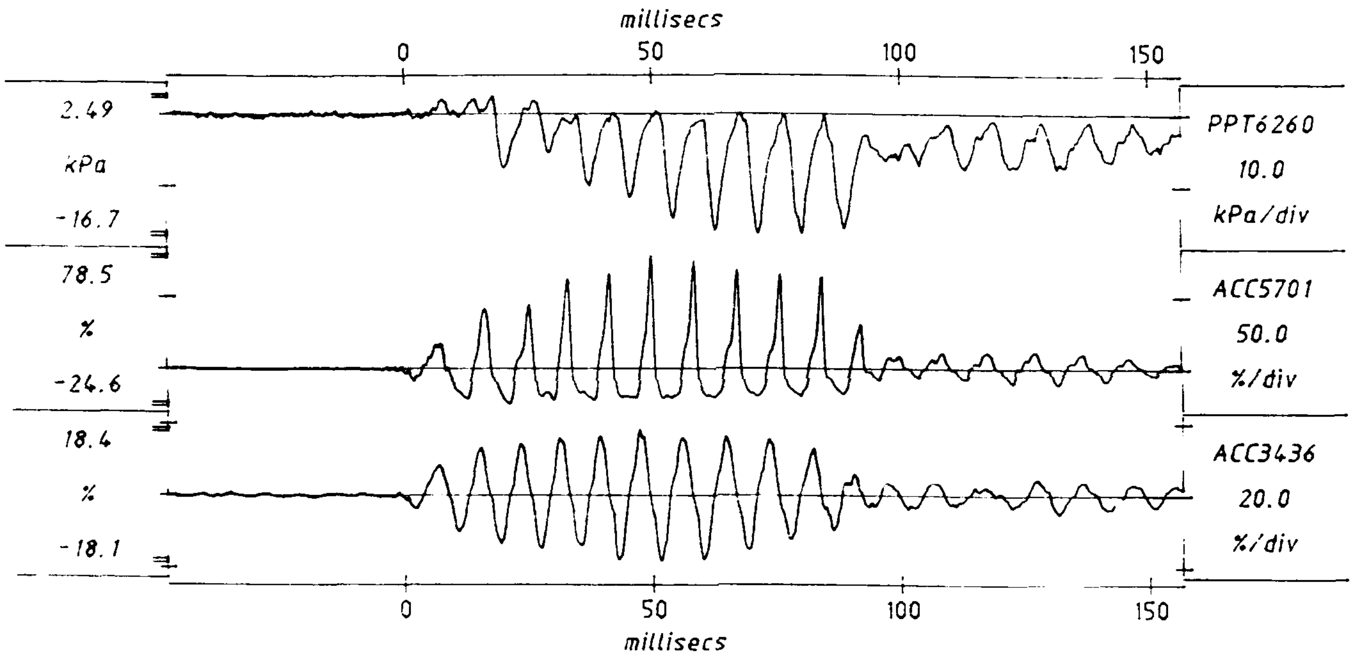
Scales : Model

TEST GEM-3 MODEL LDO FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 18.3% Kp = 19.7%	FIG. NO. 11.3



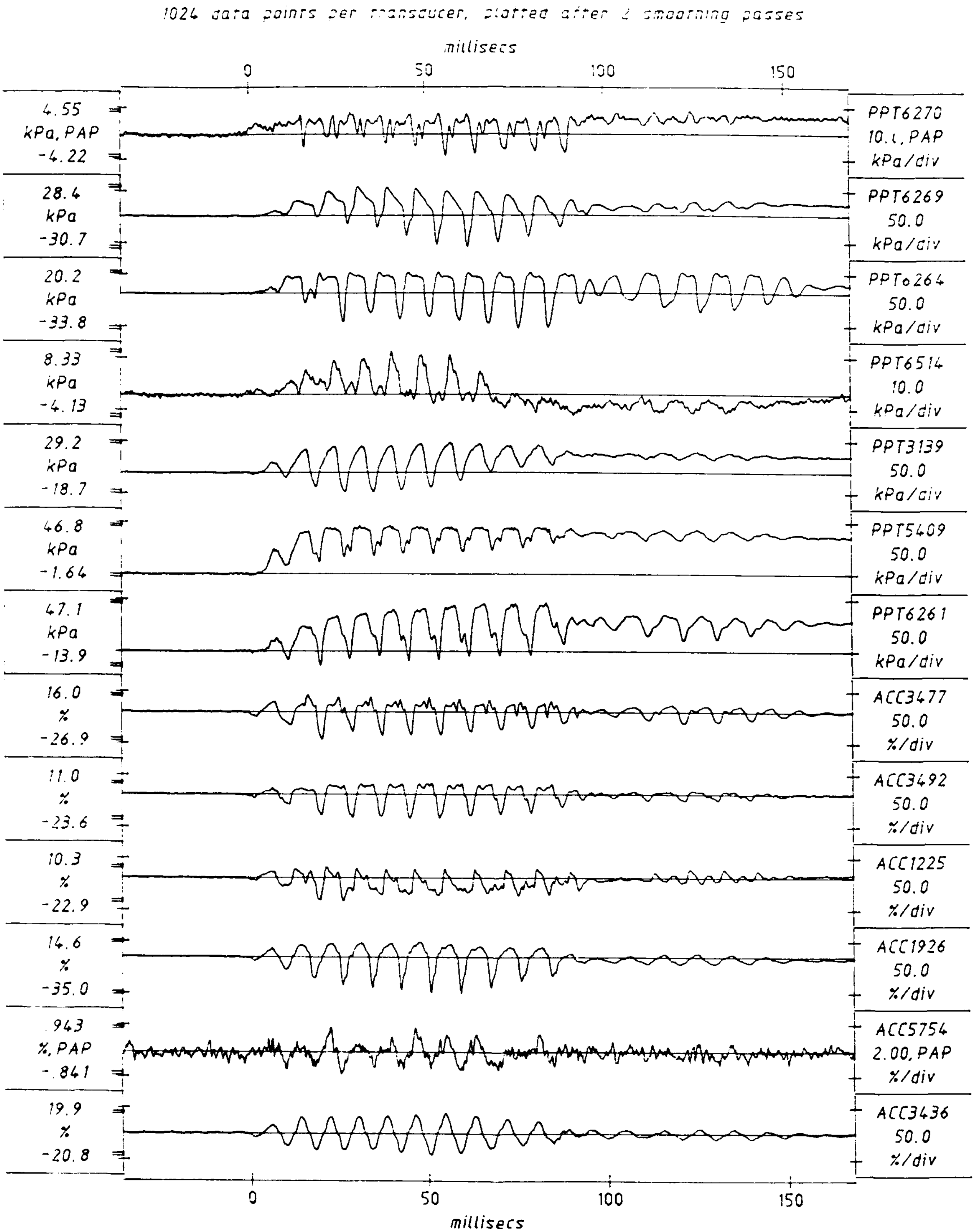
TEST GEM-3 MODEL LDO FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 17.5% Kp = 17.8%	FIG. NO. 11.4

1024 data points per transducer, plotted after 2 smoothing passes



Scales : Model

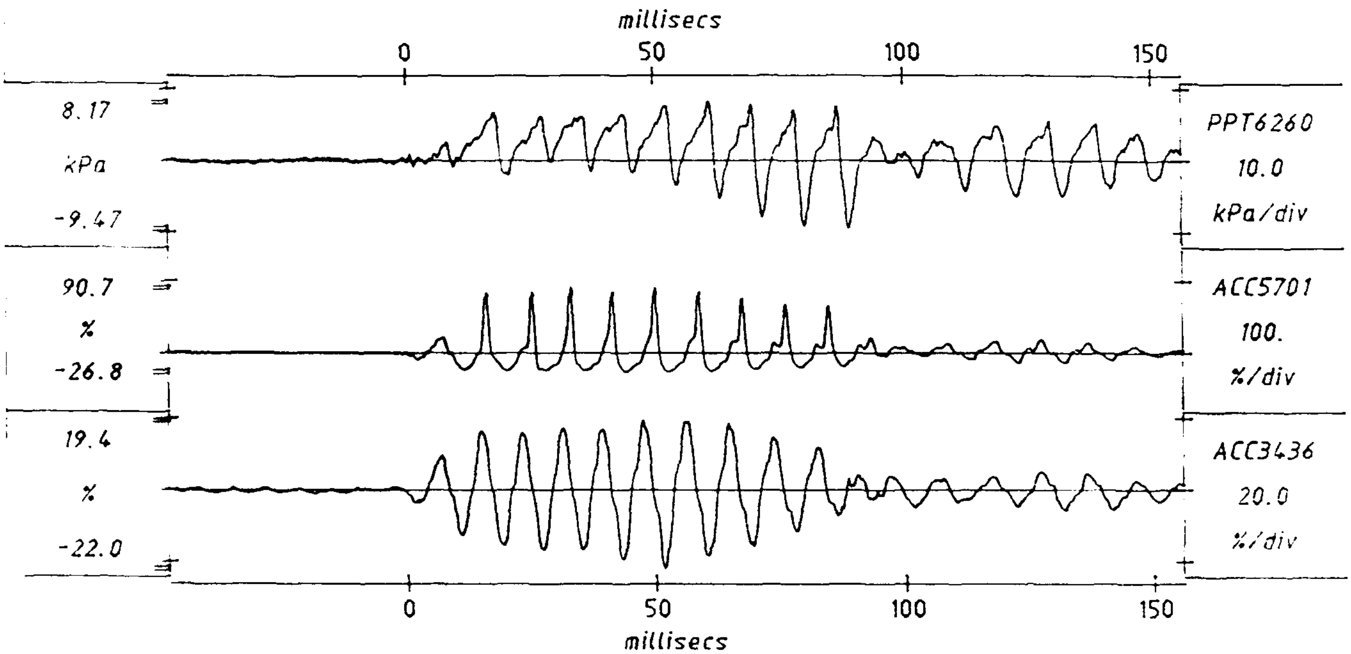
TEST GEM-3 MODEL LDO EQ2 FLIGHT 1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 18.3% Kp = 18.4%	FIG.NO. 11.5



Scales : Model

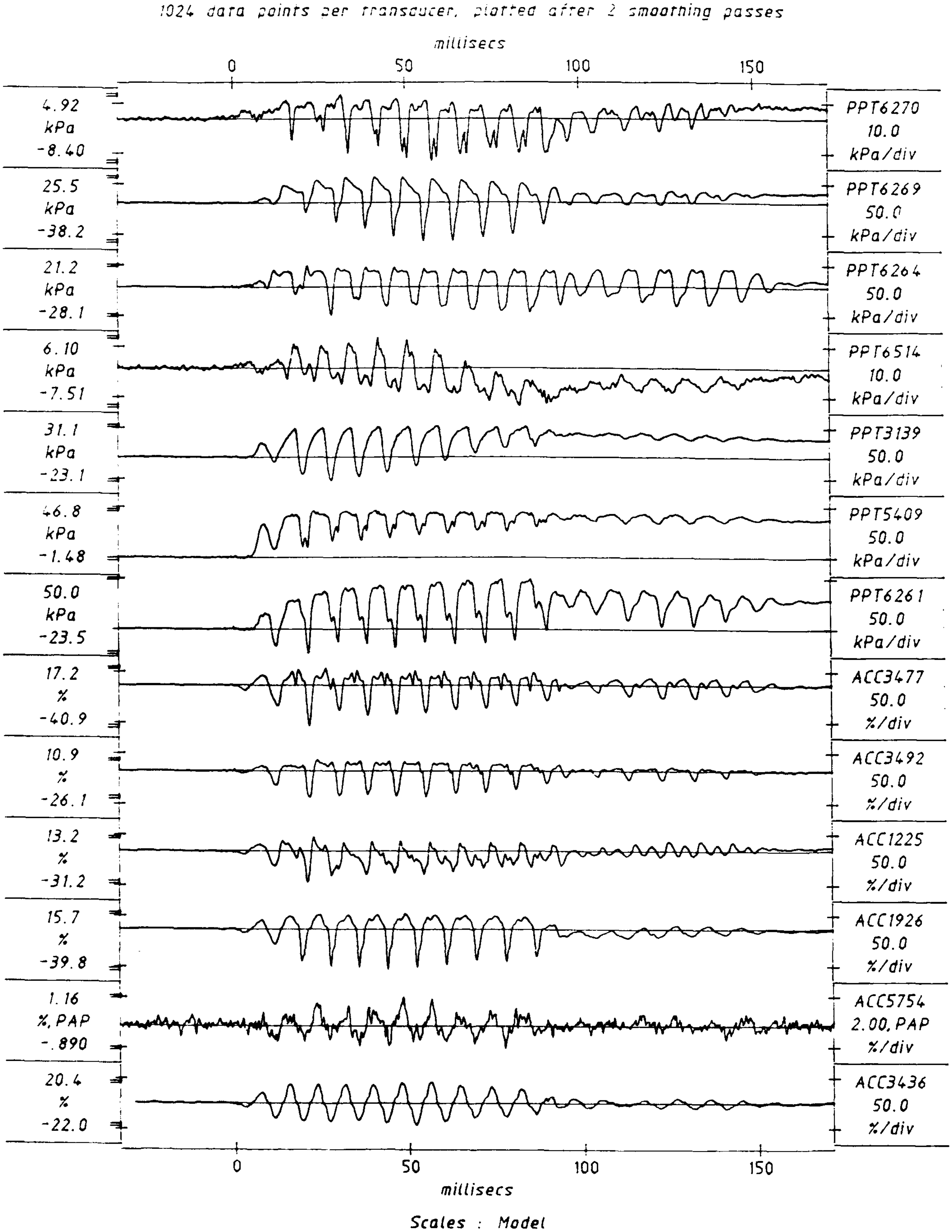
TEST GEM-3 MODEL LDO FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 20.3% Kp = 20.8%	FIG. NO. 11.6

1024 data points per transducer, plotted after 2 smoothing passes



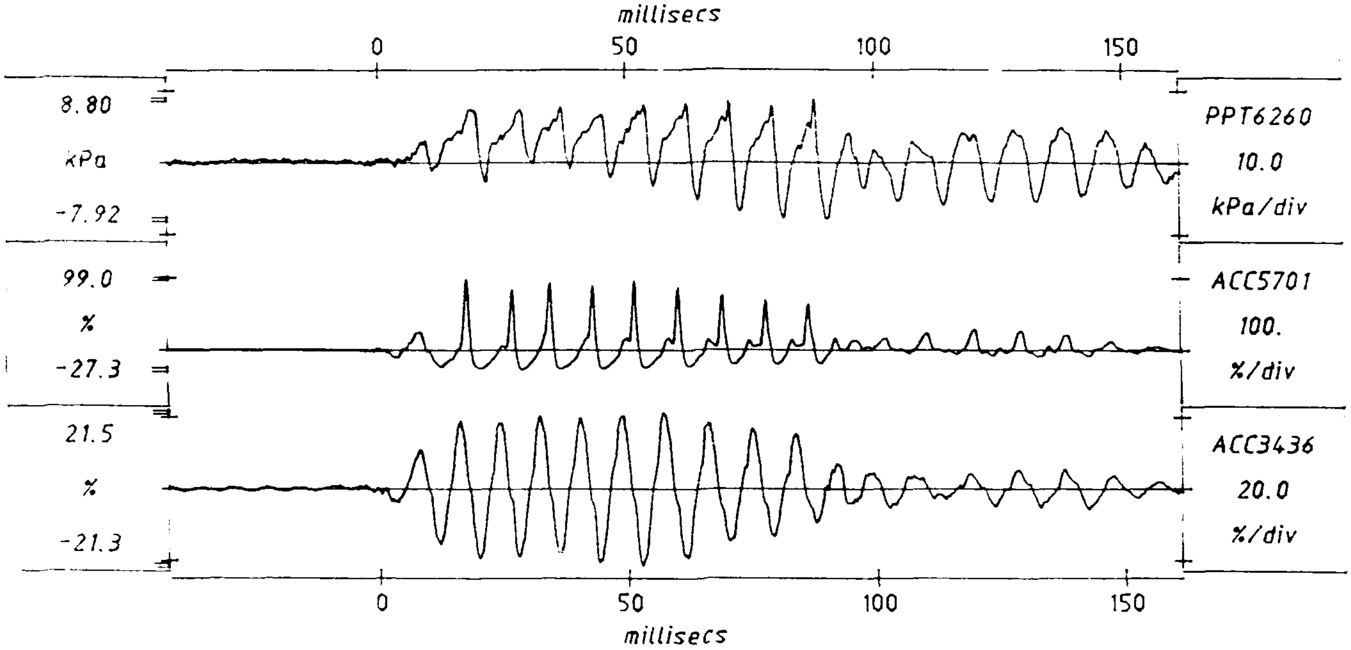
Scales : Model

TEST GEM-3 MODEL 100 FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 20.7% Kp = 22.0%	FIG. NO. 11.7



TEST GEM-3 MODEL LDO FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 21.2% Kp = 22.0%	FIG. NO. 11.8

1024 data points per transducer, plotted after 2 smoothing passes



Scales : Model

TEST GEM-3 MODEL LDO FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 21.4% Kp = 21.5%	FIG. NO. 11.9

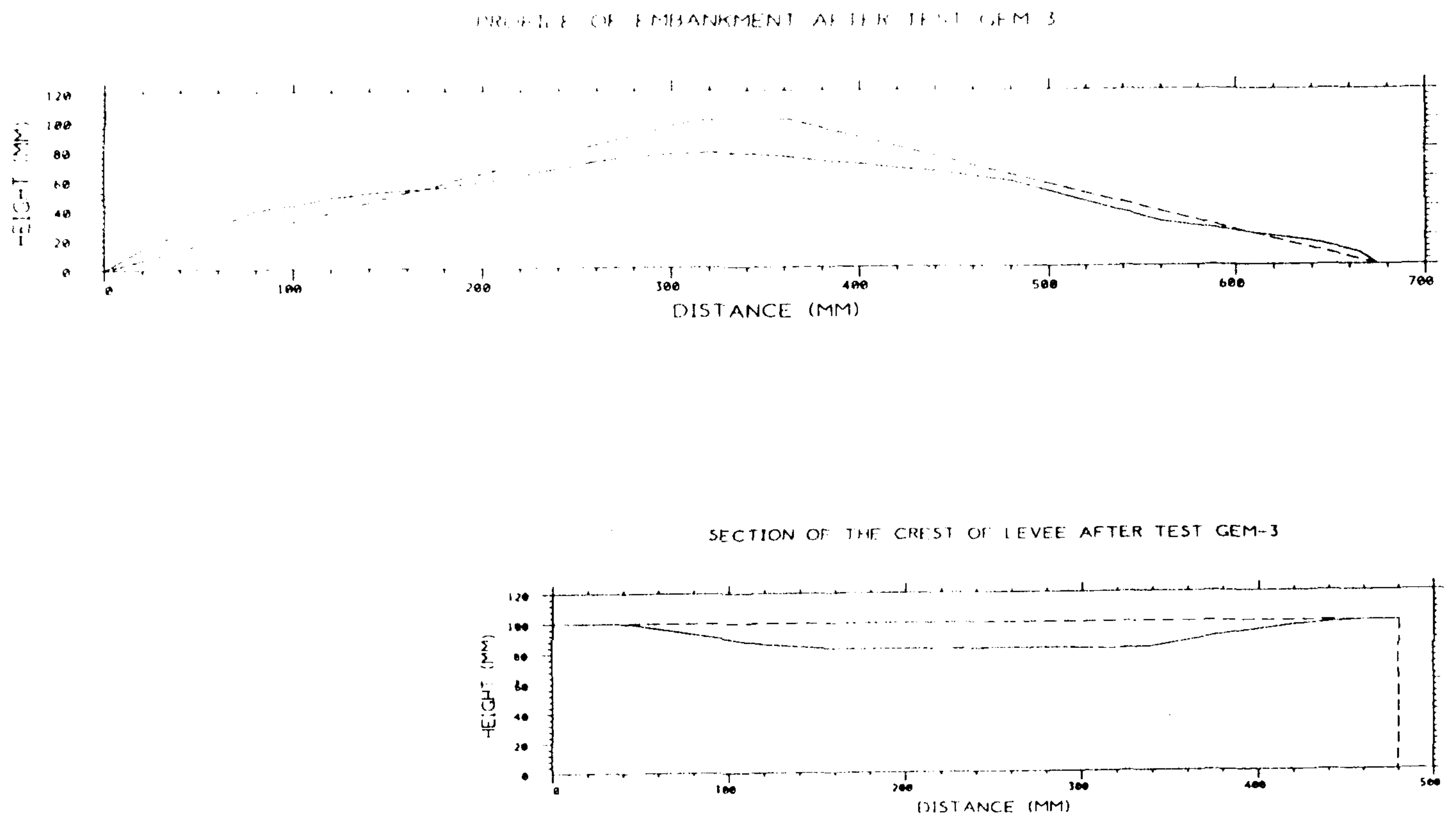


Fig.11.10 Post test longitudinal and sectional profile of model GEM-3

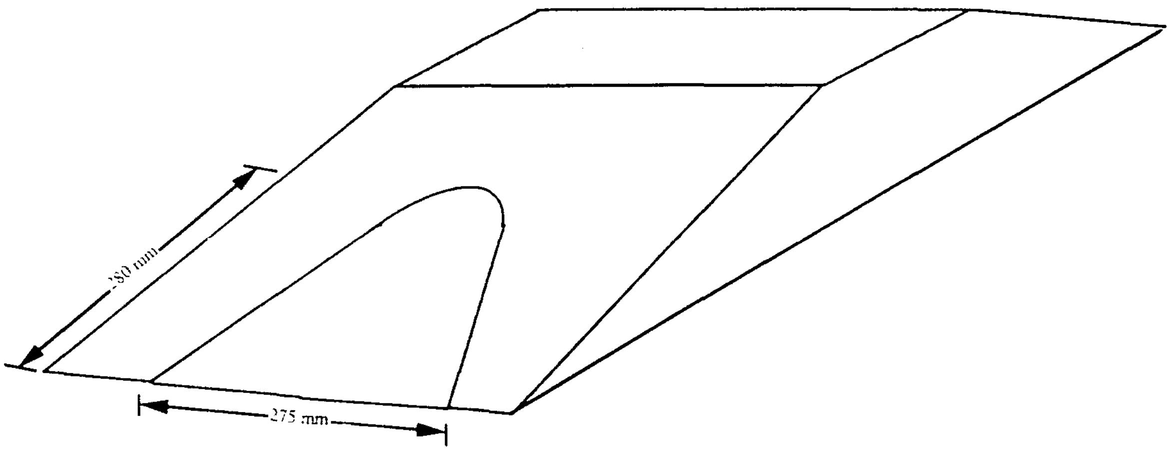


Fig. 11.11 Concoidal failure slip zone observed
in centrifuge test GEM-3 on the loose
sand pocket side of the model

GEM - 4

12 Centrifuge test GEM-4

12.1 Configuration of the test

A schematic section of the centrifuge model GEM-4 is presented in Fig.12.1a. The location of the transducers is indicated in Fig.12.1b. In this test the loose pocket had a thickness of 40 mm and was 135 mm long. The loose section was placed along the width of the strong box and was 480 mm wide. The silicone oil with a viscosity of 80 cS was used as pore fluid and the level of the oil sea was kept plush with the crest of the levee.

12.2 Construction of the model

The dense section to the left and right of the loose pocket of sand shown in Fig.12.1a was constructed by raining of LB 52/100 sand through a sand hopper. Former plates were fixed in position using paper wedges. Latex rubber sheets were placed on the sides of the loose pockets to prevent the dissipation of excess pore pressure. At the end of phase I of construction described in section 4.0 thin Lasagne sheets which were softened by saturation were placed on the upper surface of the loose pocket of sand (see Fig.12.1a). Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was completed.

12.3 Test data

Four earthquakes were fired on this model. The box acceleration was recorded by ACC 3436. The strength of the earthquake was increased from 15.1 % in the first earthquake to 27.4 % in the fourth earthquake. Large excess pore pressures were generated within the model levee and are recorded by various PPT's indicated in Fig.12.1b. The centrifuge test data is presented in Figs.12.2 to 12.10. After the centrifuge test the final profile of the levee was measured and post test investigations were conducted. The final profile of the levee after the test is presented if Fig.12.11.

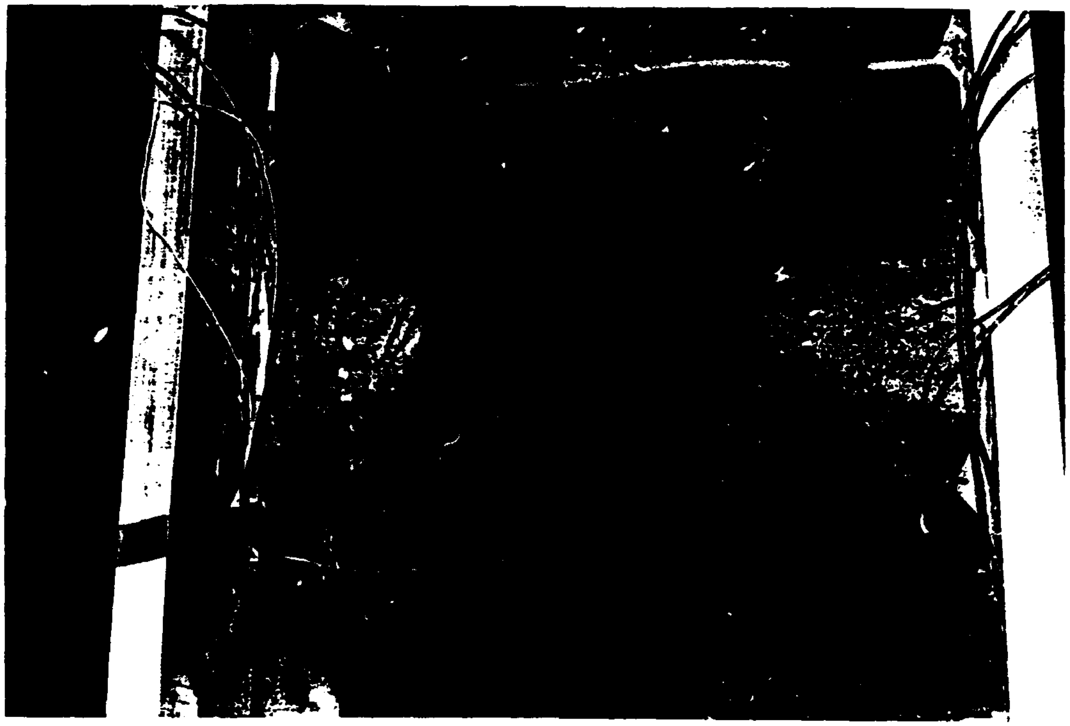


Plate 12.1 Uneven settlement along the cross section of the model GEM-4 (Plan View)

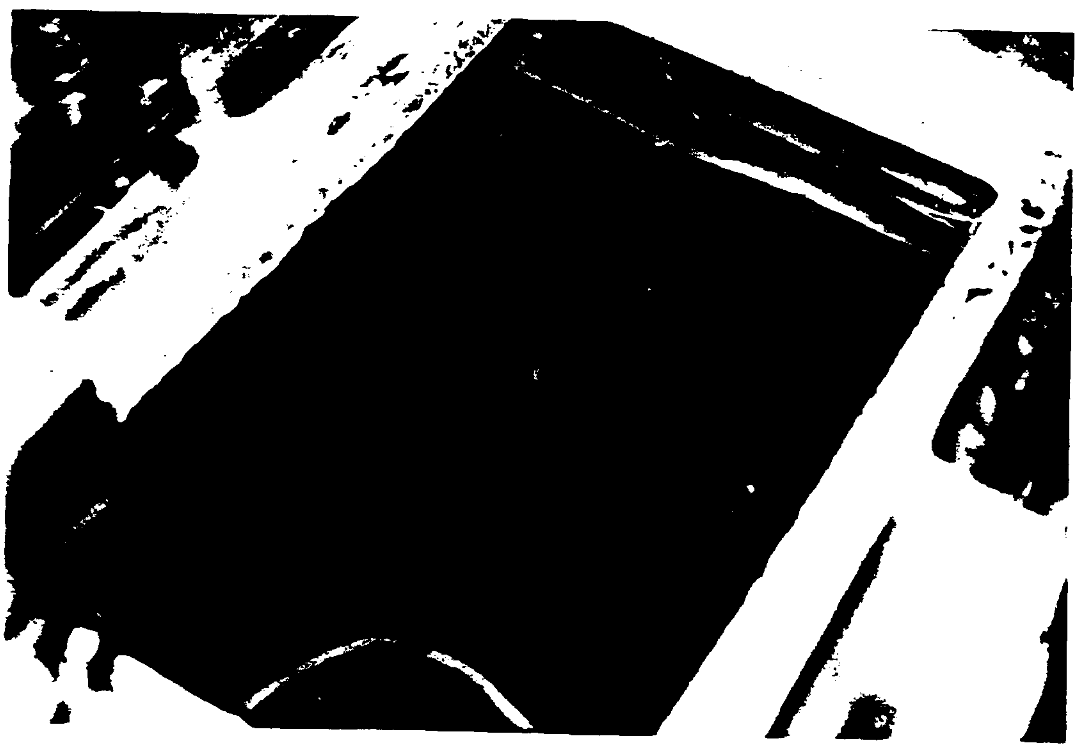


Plate 12.2 Slipping of the levee slope

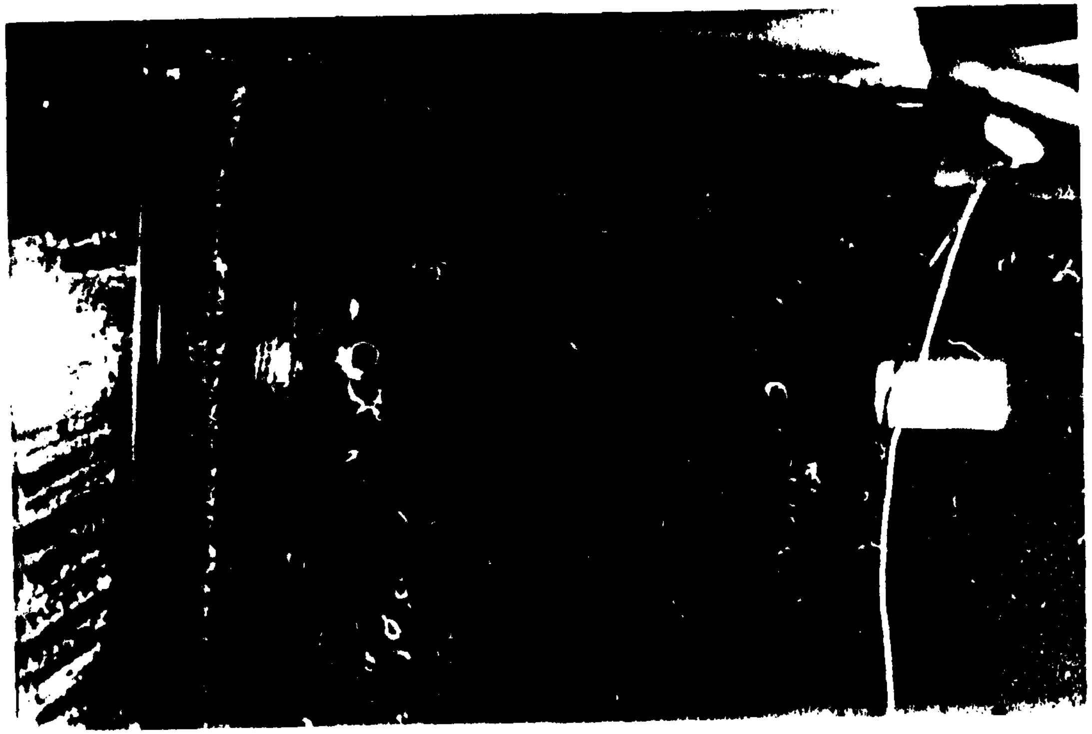
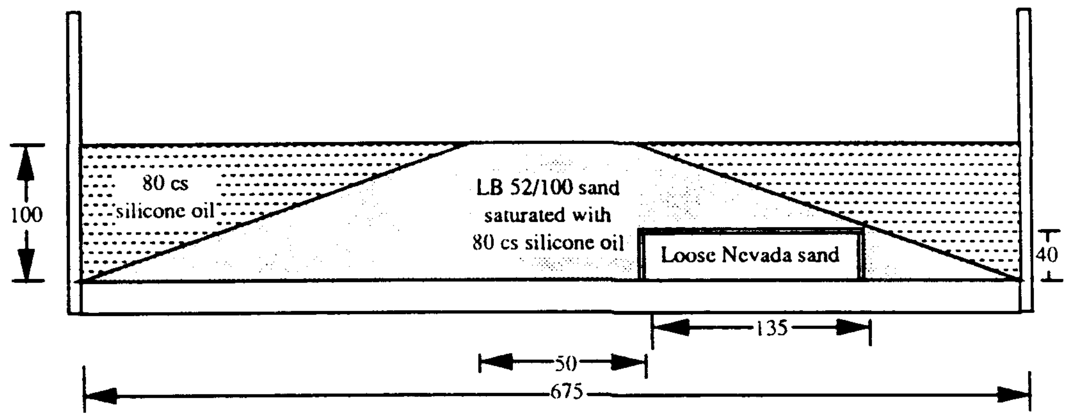
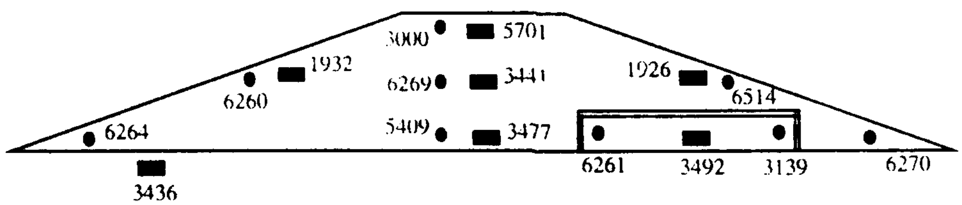


Plate 12.3 Release of excess pore pressures due to opening up of Lasagne sheet (Plan view)

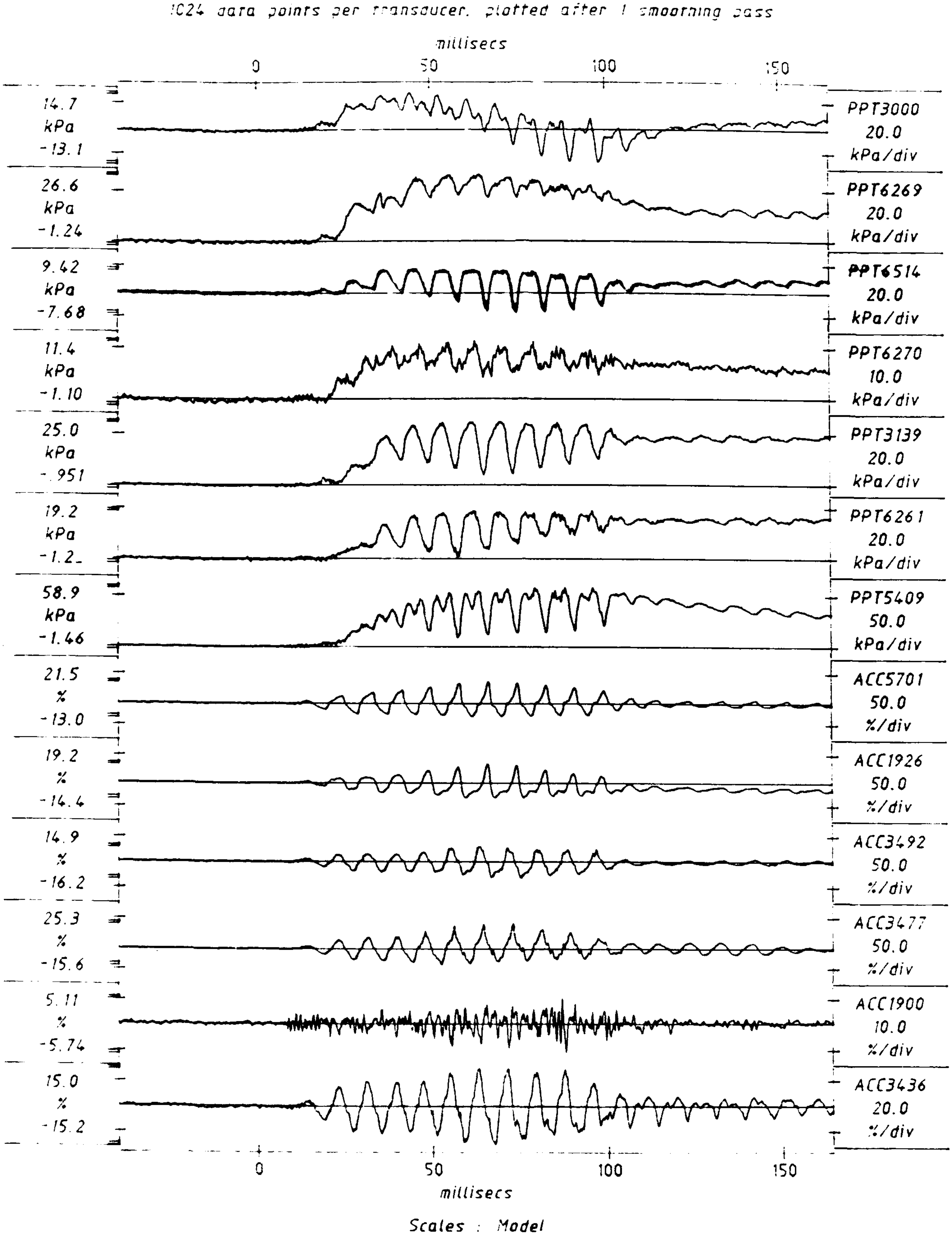


A) Schematic section of centrifuge model GEM-4



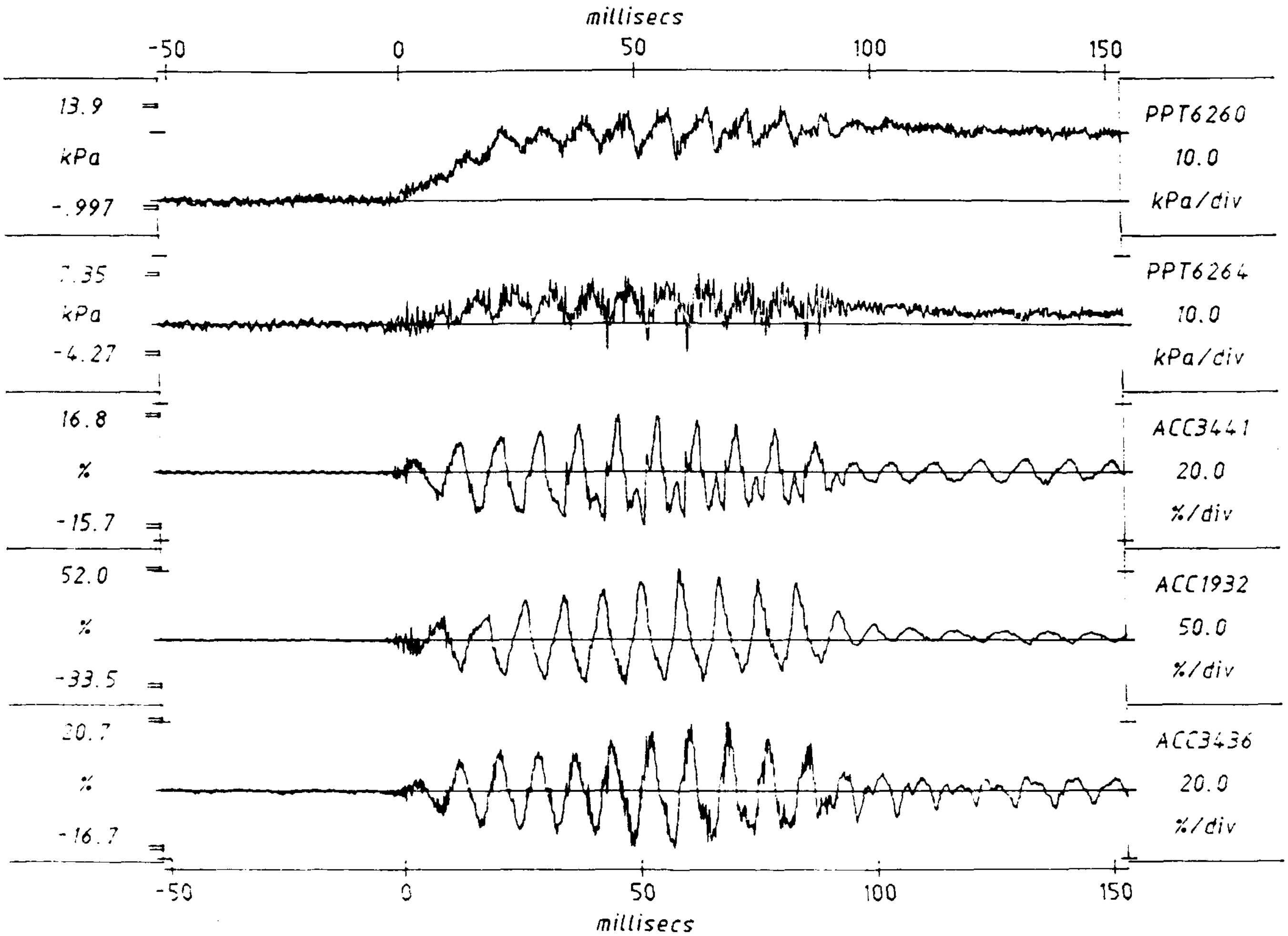
B) Placement of transducers in centrifuge test GEM-4

FIG. 12.1



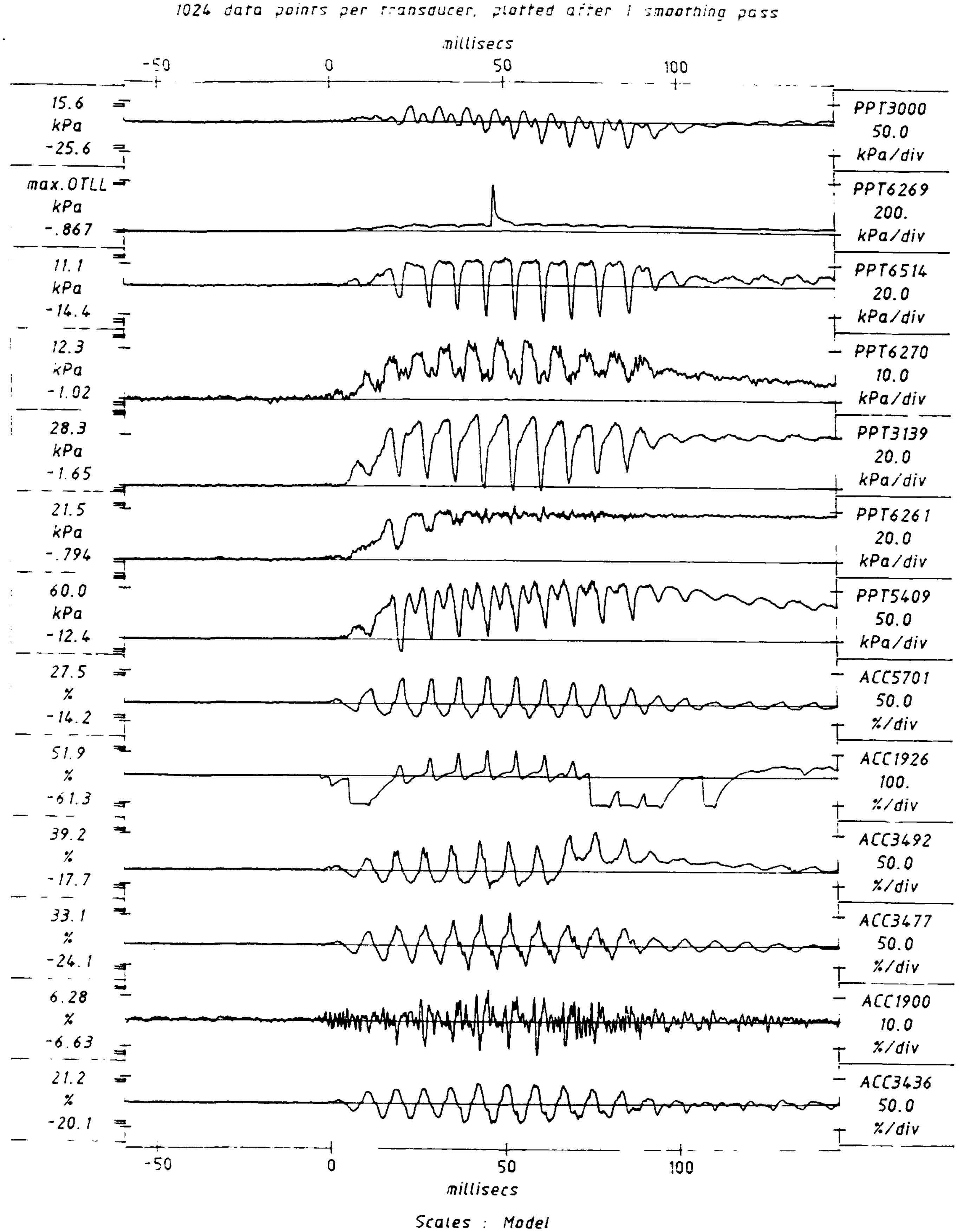
TEST GEM-4 MODEL LDO FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g $K\pi$ = 15.1% Kp = 15.2%	FIG. NO 12.2

1024 raw data points plotted per transducer



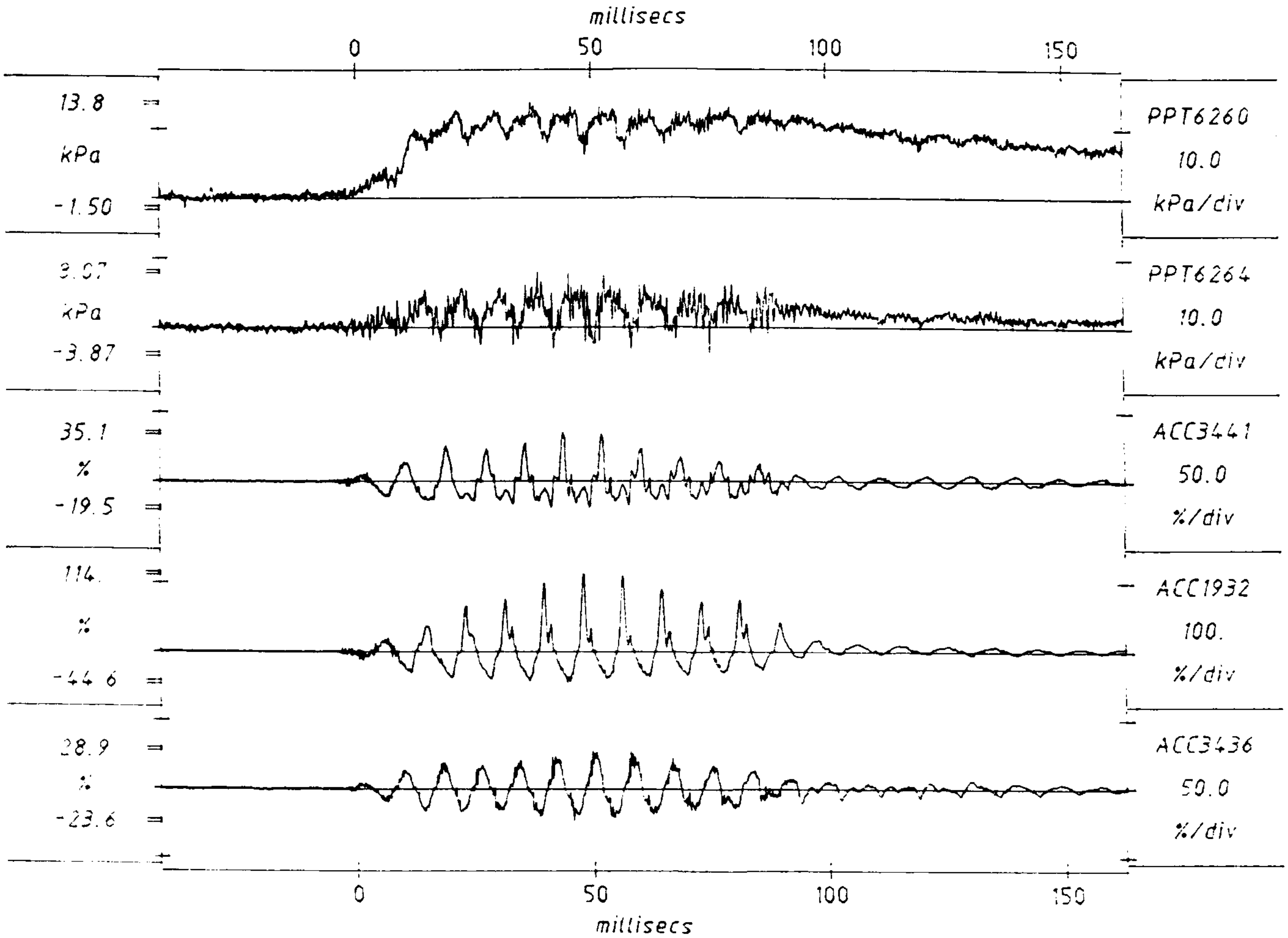
Scales · Model

TEST GEM-4 MODEL 100 FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 18.7% Kp = 20.7%	FIG. NO. **12.3**



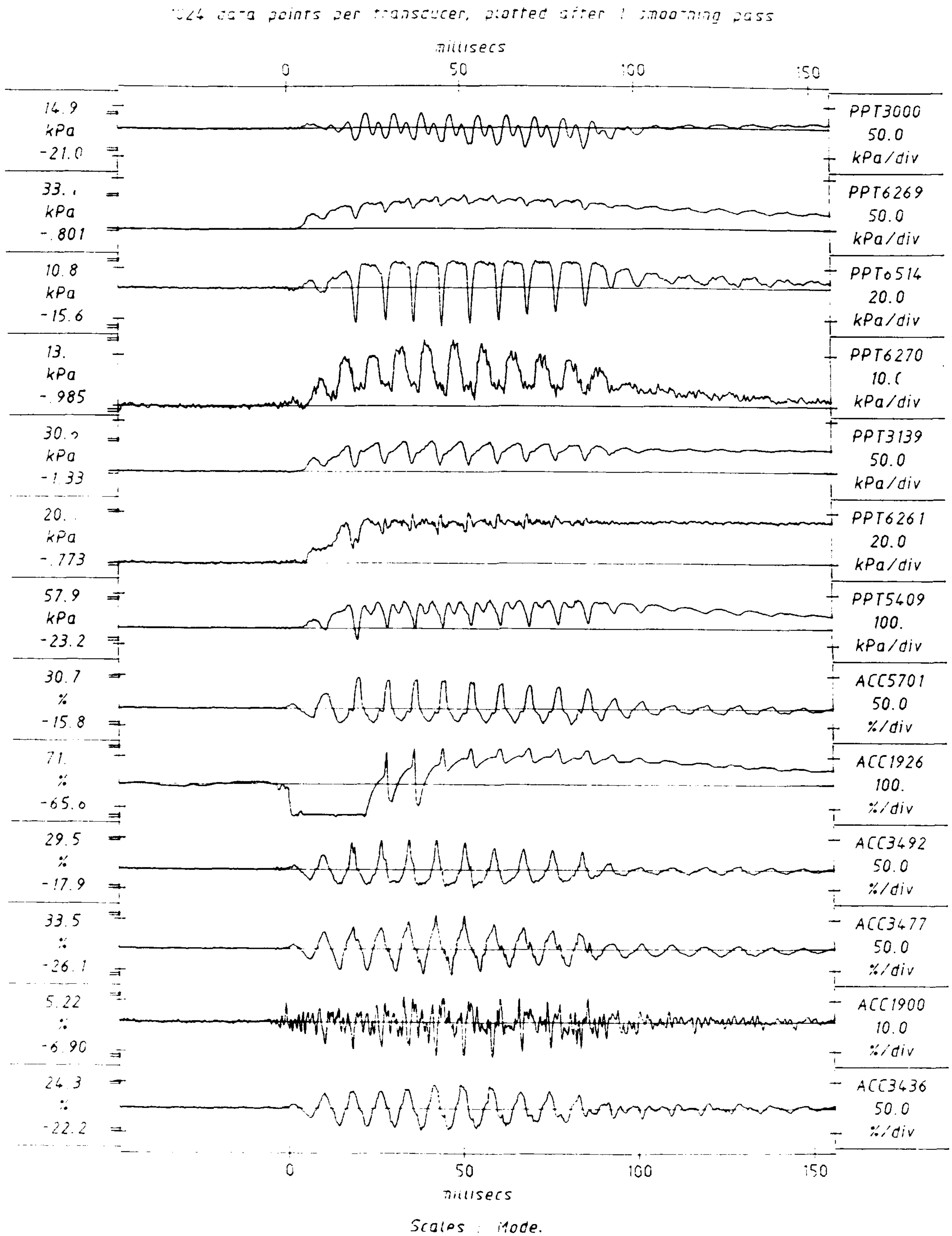
TEST GEM-4 MODEL 100 EQ2 FLIGHT 1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 20.6% Kp = 21.2%	FIG. NO. 12.4

1024 raw data points plotted per transducer



Scales : Model

TEST GEM-4 MODEL LDO FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 26.3% Kp = 28.9%	FIG. NO. 12.5



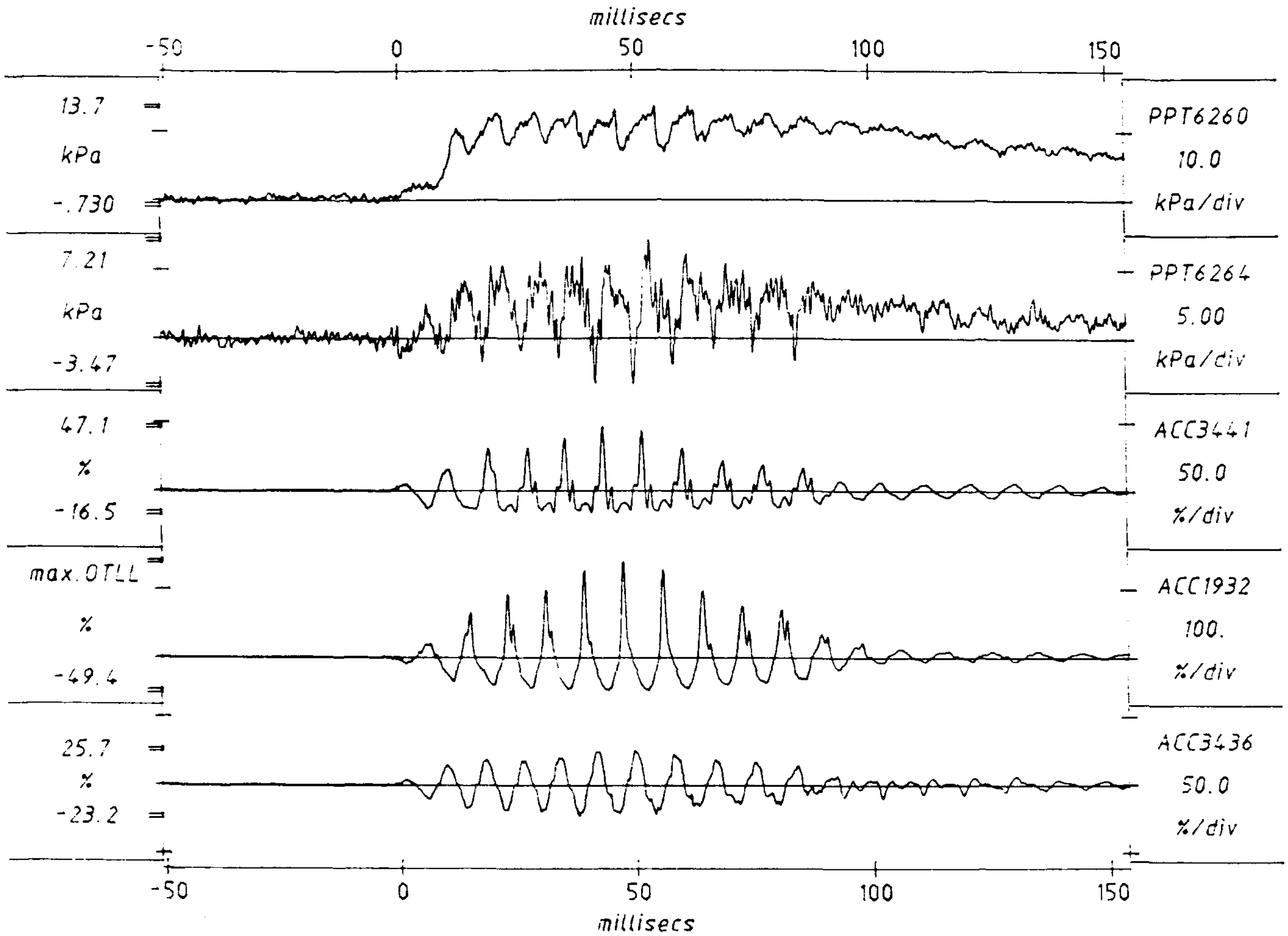
EQ3

SHORT-TERM TIME RECORDS

G = 80.0g
Km = 23.3%
Kp = 24.3%

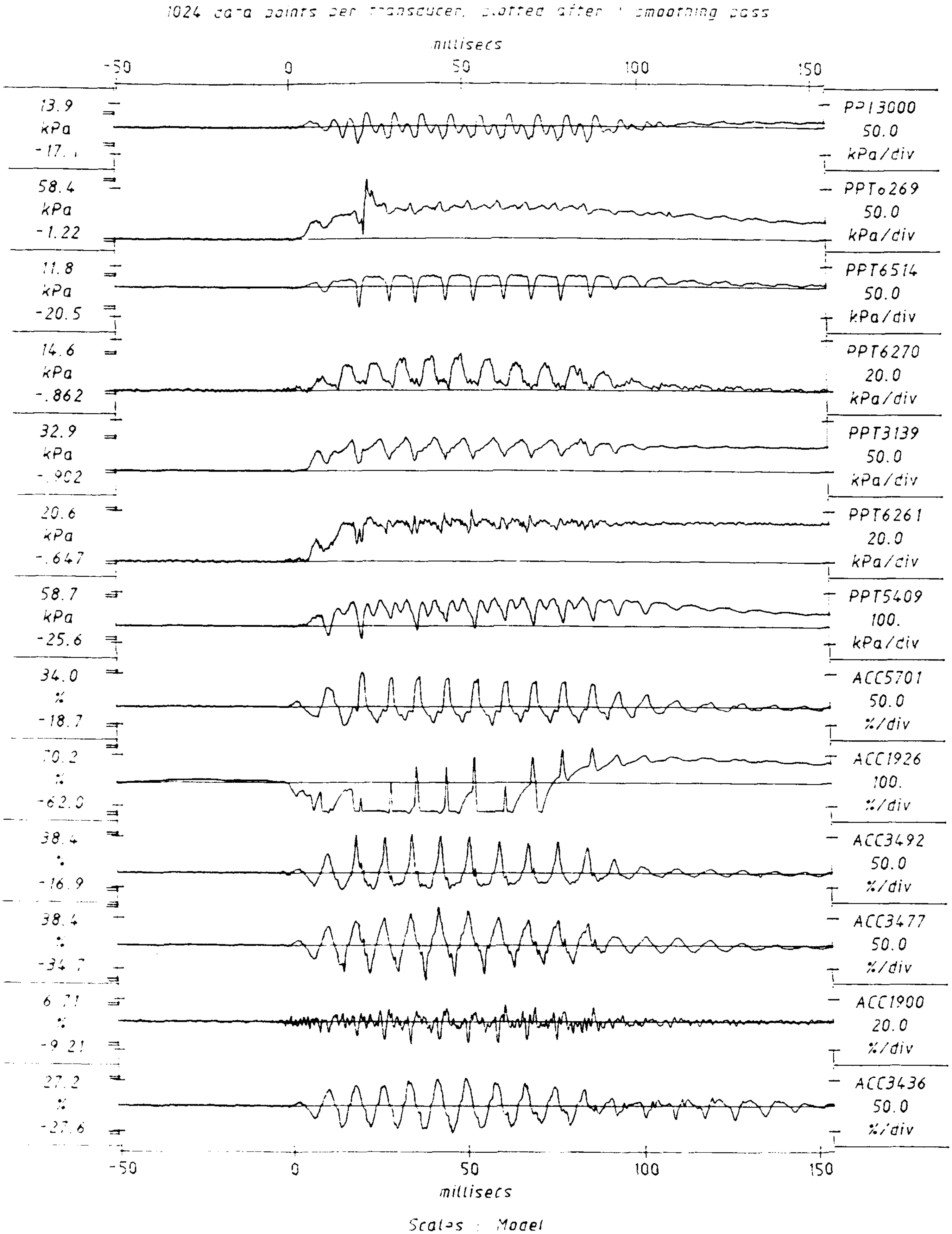
FIG. NO. 12.6

1024 data points per transducer, plotted after 1 smoothing pass



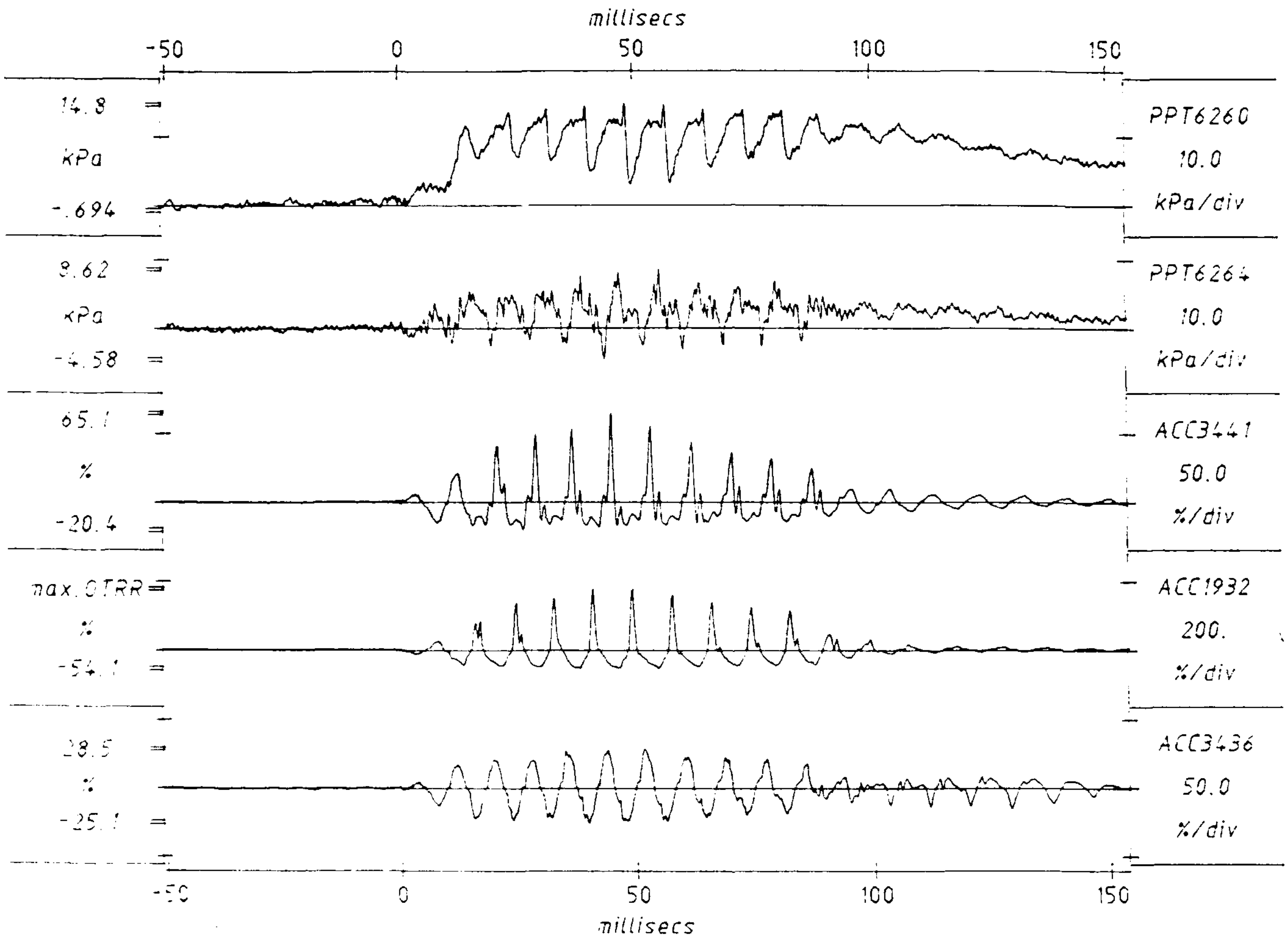
Scales : Model

TEST GEM-4 MODEL LDO FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 24.5% Kp = 25.7%	FIG.NO. 12.7



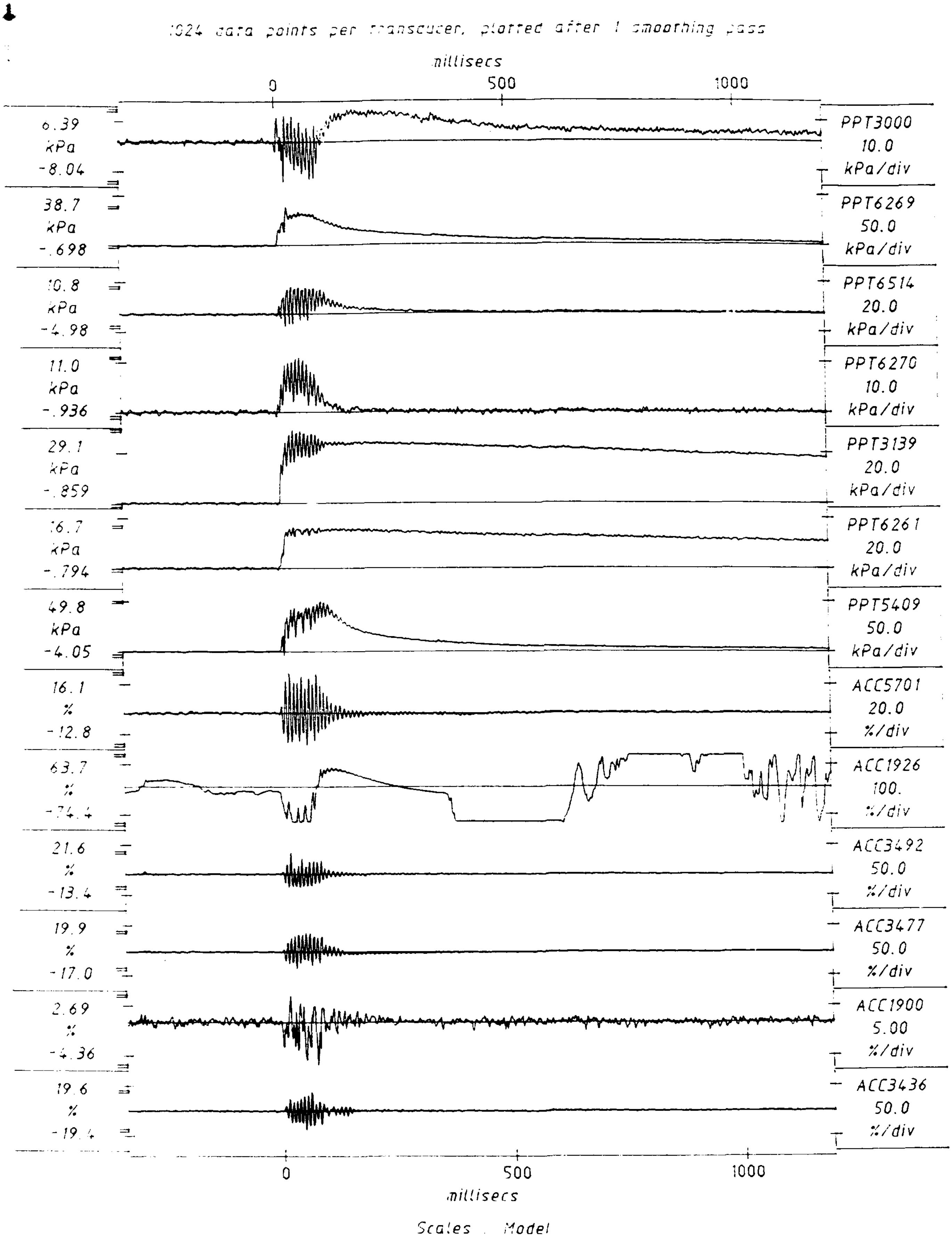
TEST GEM-4 MODEL 200 FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 27.4% Kp = 27.6%	FIG. NO. **12.8**

1024 data points per transducer, plotted after 1 smoothing pass

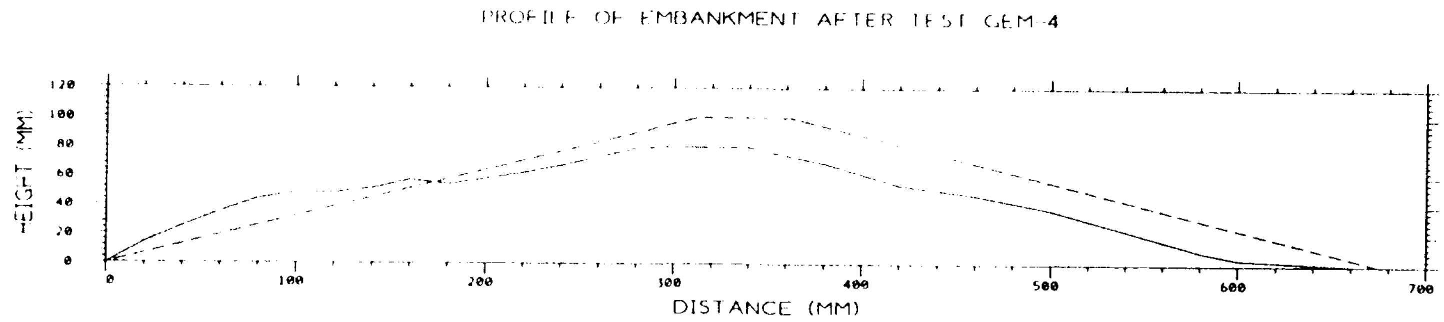


Scales : Model

TEST SEM-4 MODEL 100 FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 26.8% Kp = 28.5%	FIG.NO. **12.9**



TEST GEM-4 MODEL LDO FLIGHT 1	EQ4	LONG-TERM TIME RECORDS	G = 80.0g Km = 19.5% Kp = 19.6%	FIG. NO. 12.10



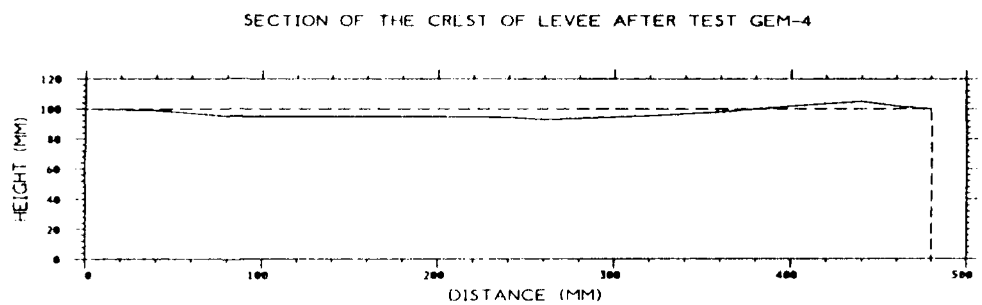


Fig.12.11 Post test longitudinal and sectional profile of model GEM-4

GEM - 5

13 Centrifuge test GEM-5

13.1 Configuration of the test

A schematic section of the centrifuge model GEM-5 is presented in Fig.13.1a. The location of the transducers is indicated in Fig.13.1b. In this test the loose pocket was triangular and formed the toe of the levee on the down stream side. The height of the loose section was 75 mm and its length was 250 mm as indicated in Fig.13.1a. The loose section was placed along the width of the strong box and was 480 mm wide. The silicone oil with a viscosity of 80 cS was used as pore fluid and the level of the oil sea was kept plush with the crest of the levee.

13.2 Construction of the model

The dense section to the left and right of the loose pocket of sand shown in Fig.13.1a was constructed by raining of LB 52/100 sand through a sand hopper. Former plates were fixed in position using paper wedges. Latex rubber sheet was placed on the left hand side of the loose pocket to prevent the dissipation of excess pore pressure. Phase I and Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was completed.

13.3 Test data

Four earthquakes were fired on this model. The box acceleration was recorded by ACC 3436. The strength of the earthquake was increased from 17.1 % in the first earthquake to 27.3 % in the fourth earthquake. Large excess pore pressures were generated within the model levee and are recorded by various PPT's indicated in Fig.13.1b. The centrifuge test data is presented in Figs.13.2 to 13.11. Long term records for earthquakes 1 and 4 are presented in Figs. 13.4 and 13.11 respectively. After the centrifuge test the final profile of the levee was measured and post test investigations were conducted. The final profile of the levee after the test is presented if Fig.13.12.

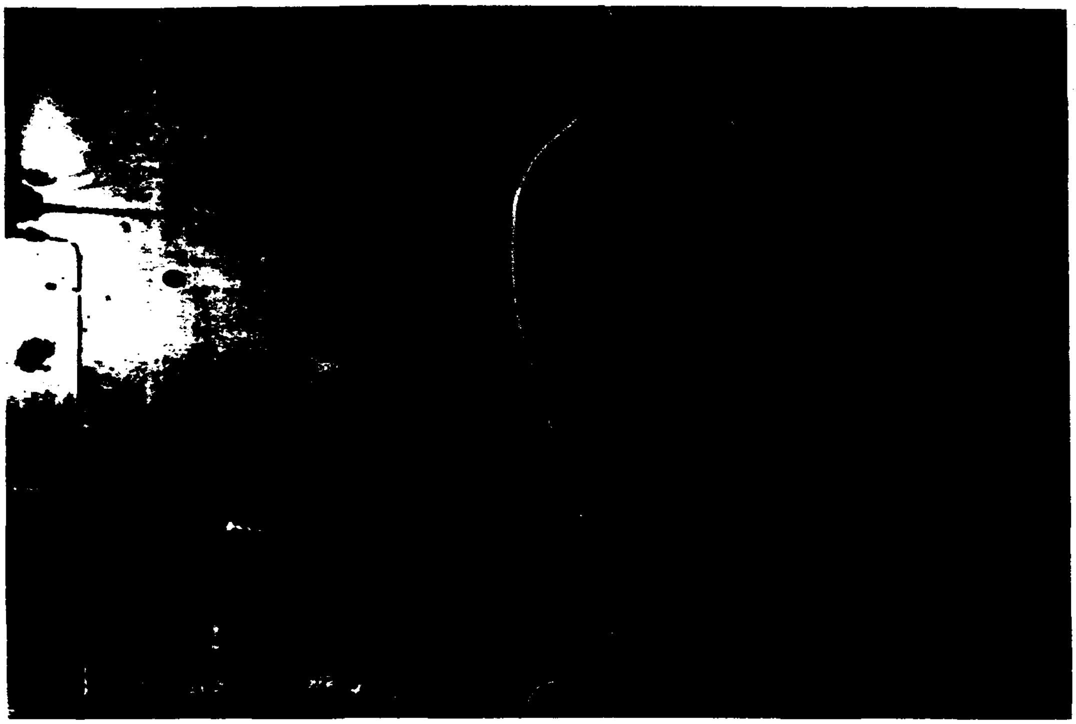


Plate 13.1 Placement of transducers in centrifuge test GEM-5

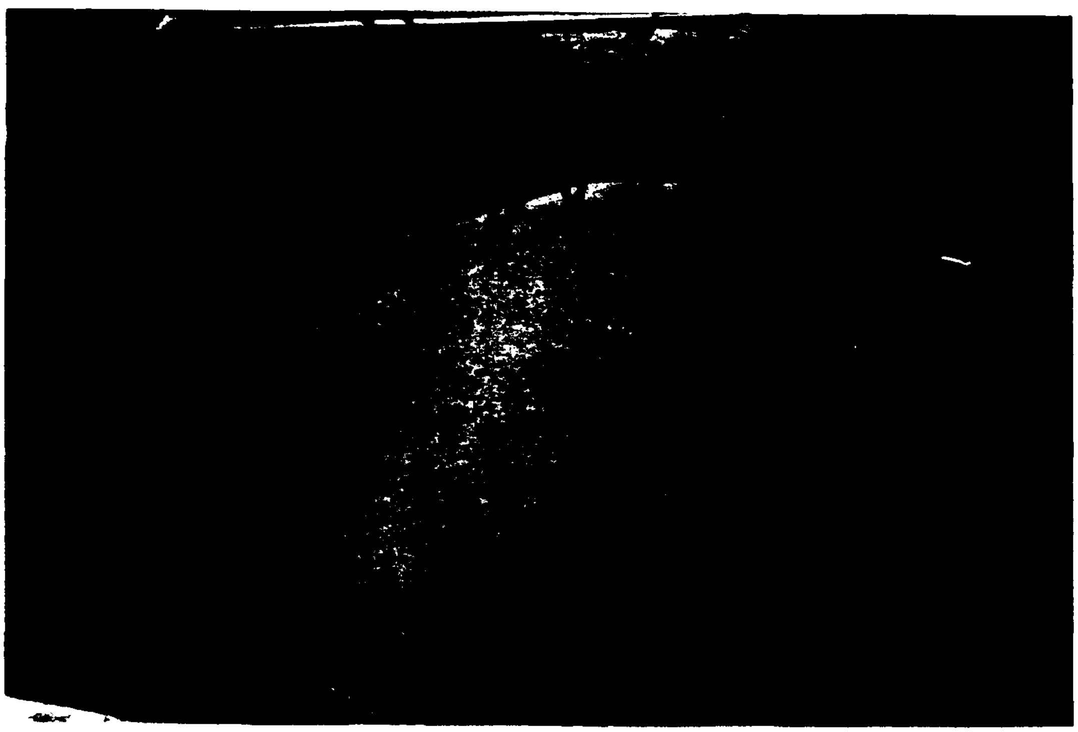
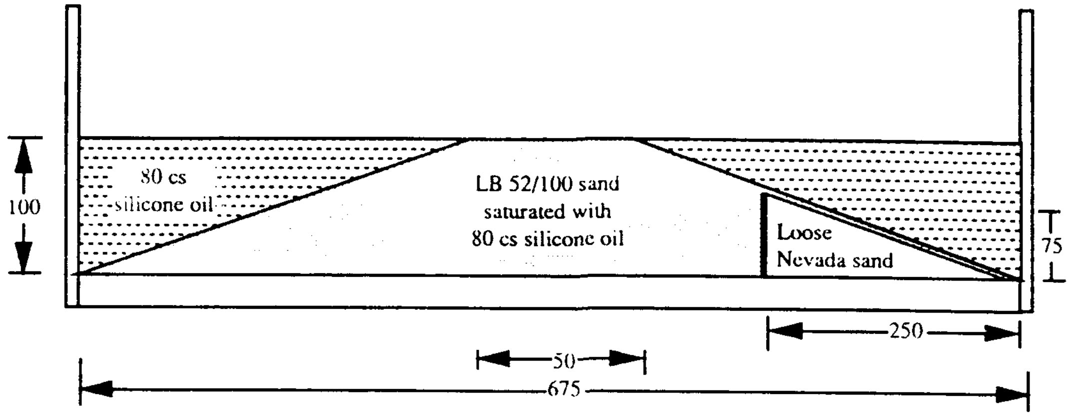


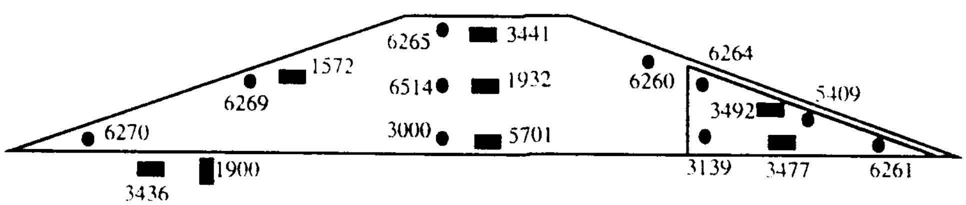
Plate 13.2 Final profile before saturation

Plate 13.3 Floating of PPT's due to liquefaction of soil

Plate 13.4 Sand boils formed due to liqefaction
(at top left hand corner and along the left hand edge)

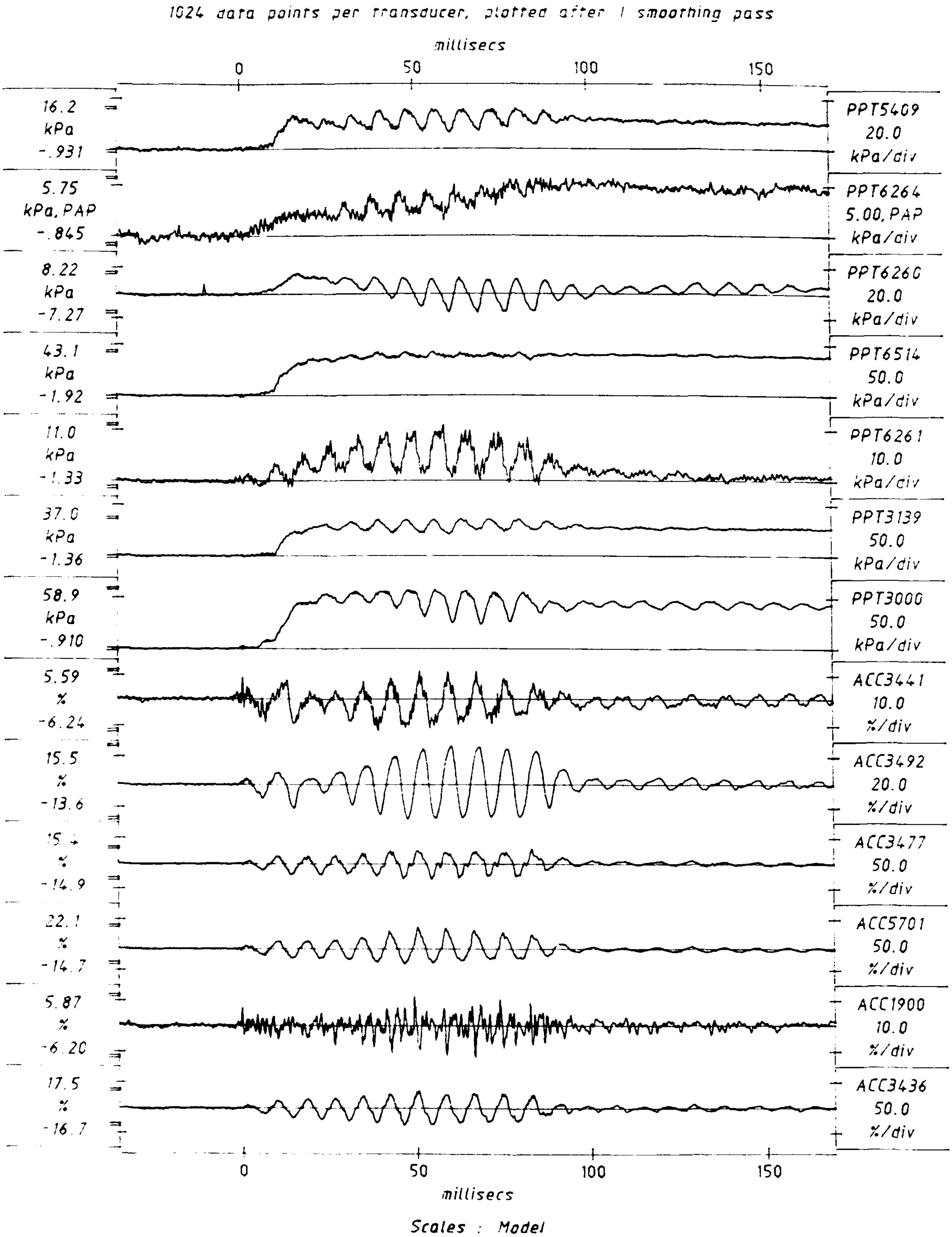


A) Schematic section of centrifuge model GEM-5



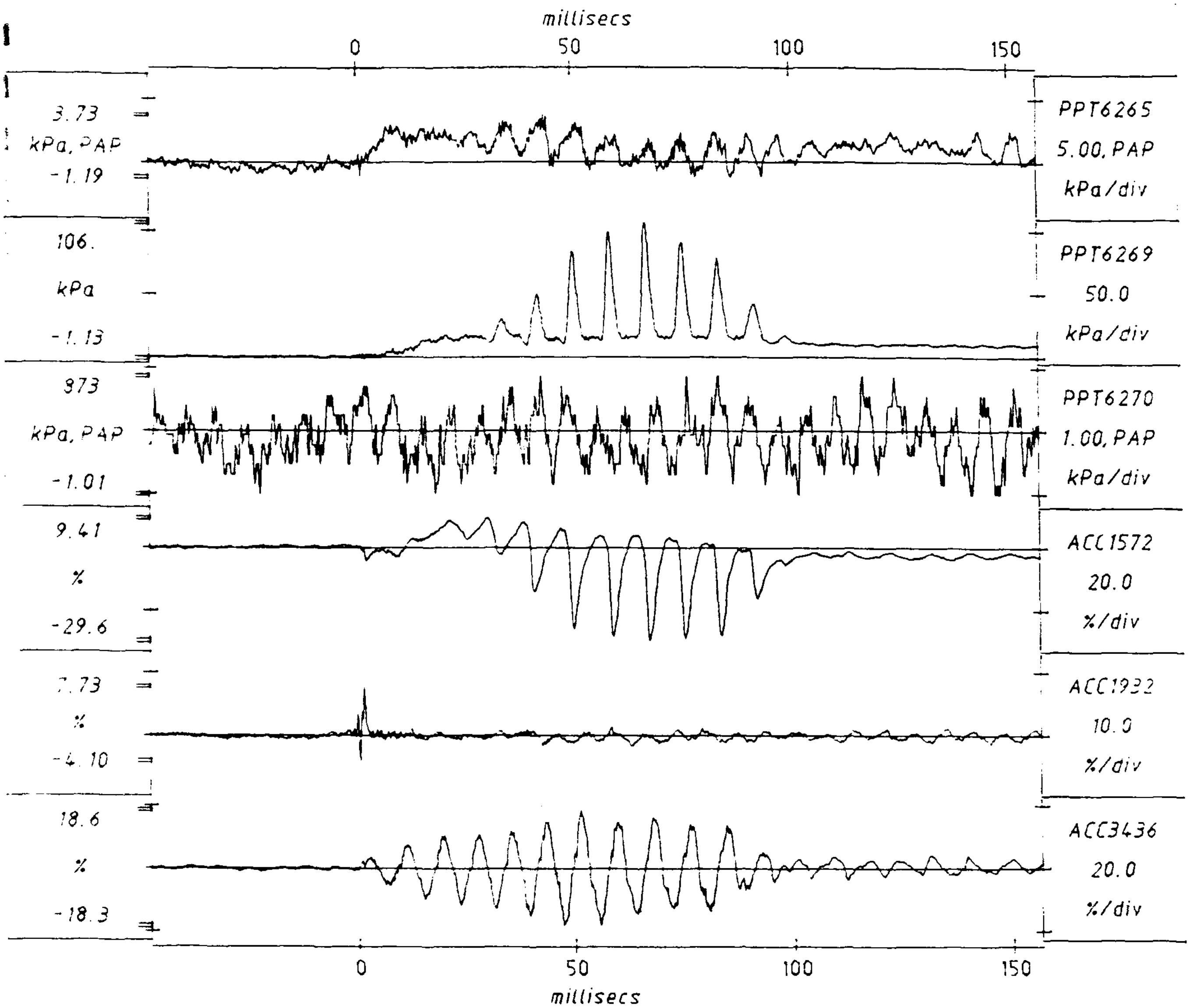
B) Placement of transducers in centrifuge test GEM-5

FIG. 13.1



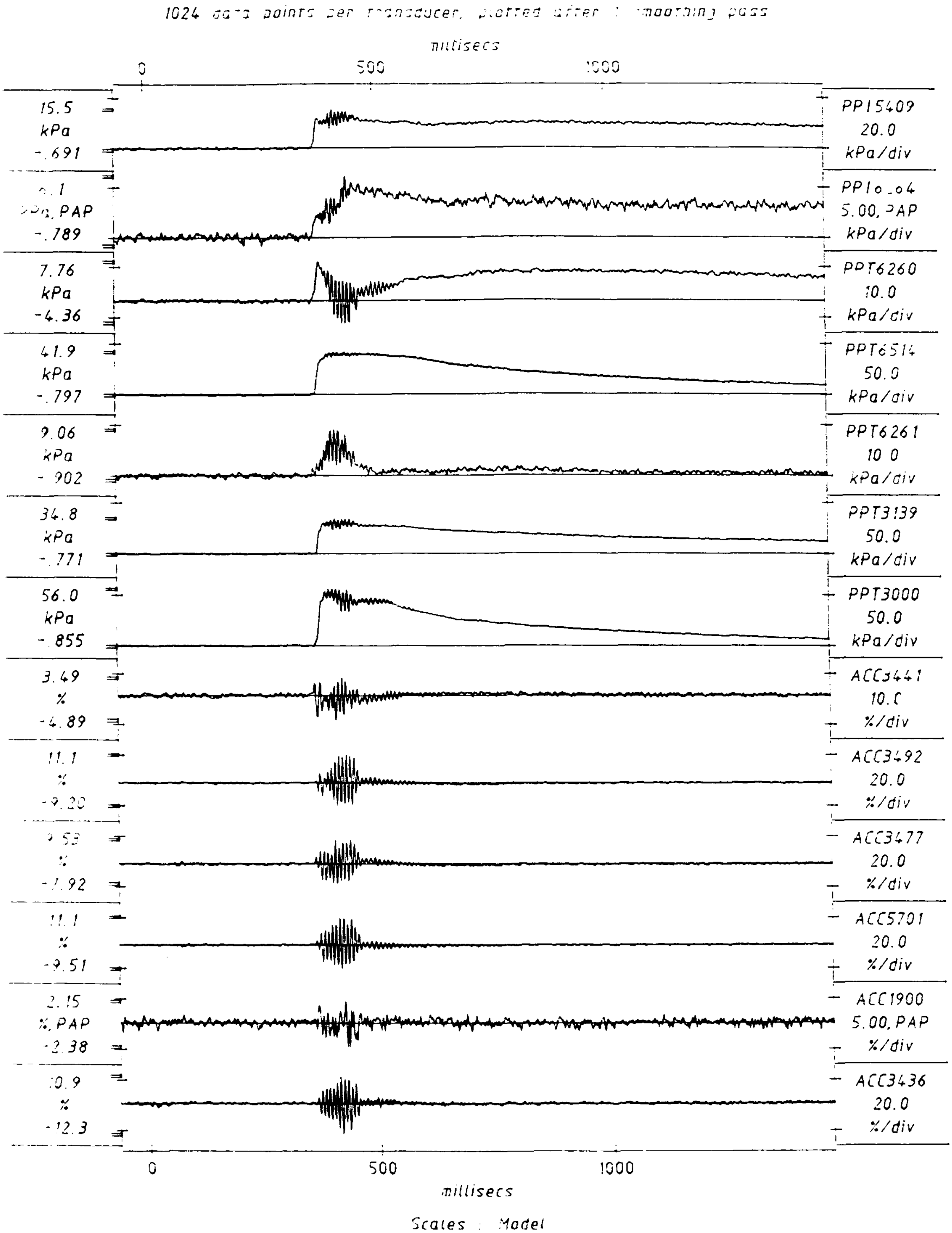
TEST GEM-5 MODEL LDO FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 17.1% Kp = 17.5%	FIG. NO. 13.2

1024 data points per transducer, plotted after 1 smoothing pass

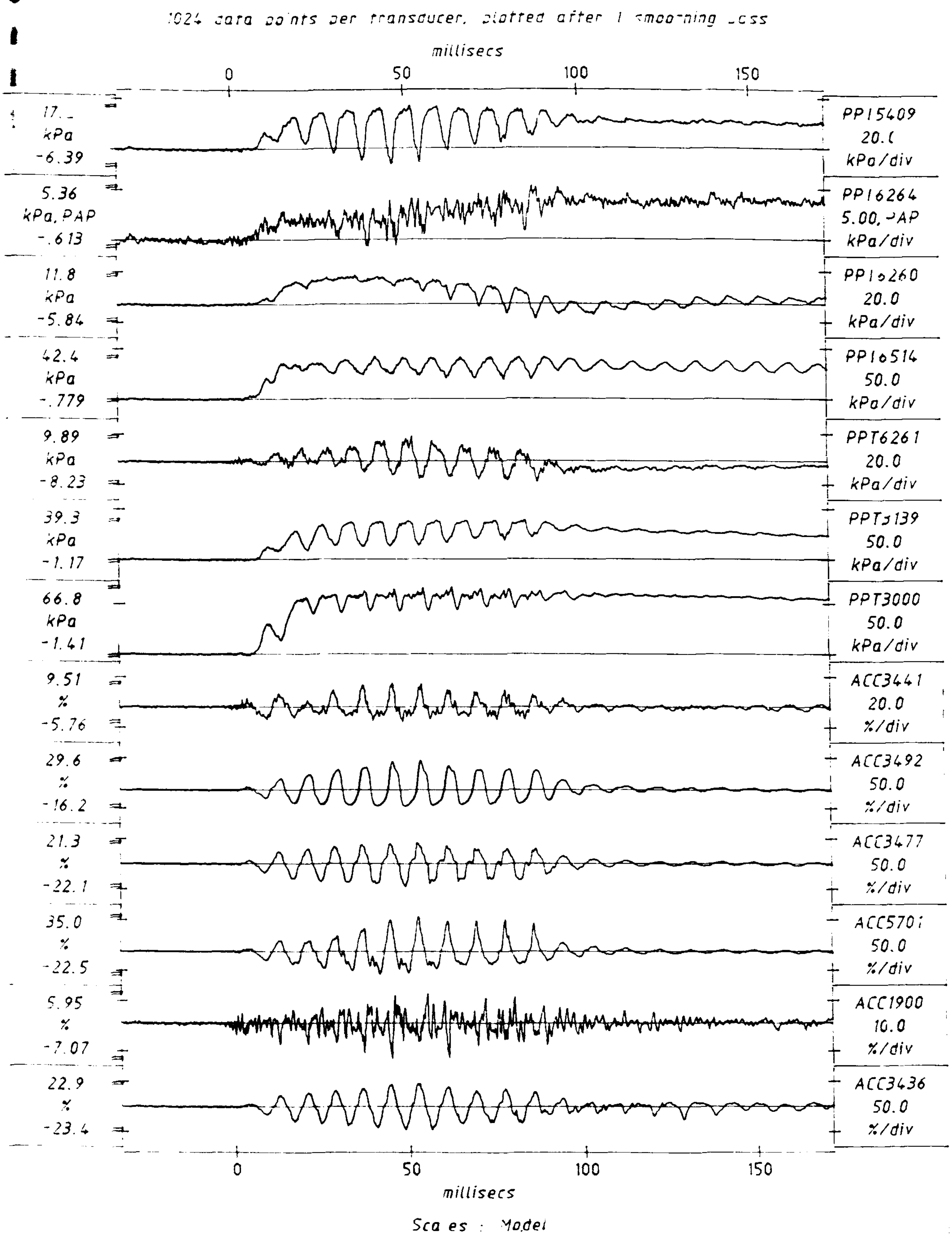


Scales : Model

TEST GEM-5 MODEL _DO EQ1 FLIGHT 1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 18.4% Kp = 18.6%	FIG. NO. **13.3**

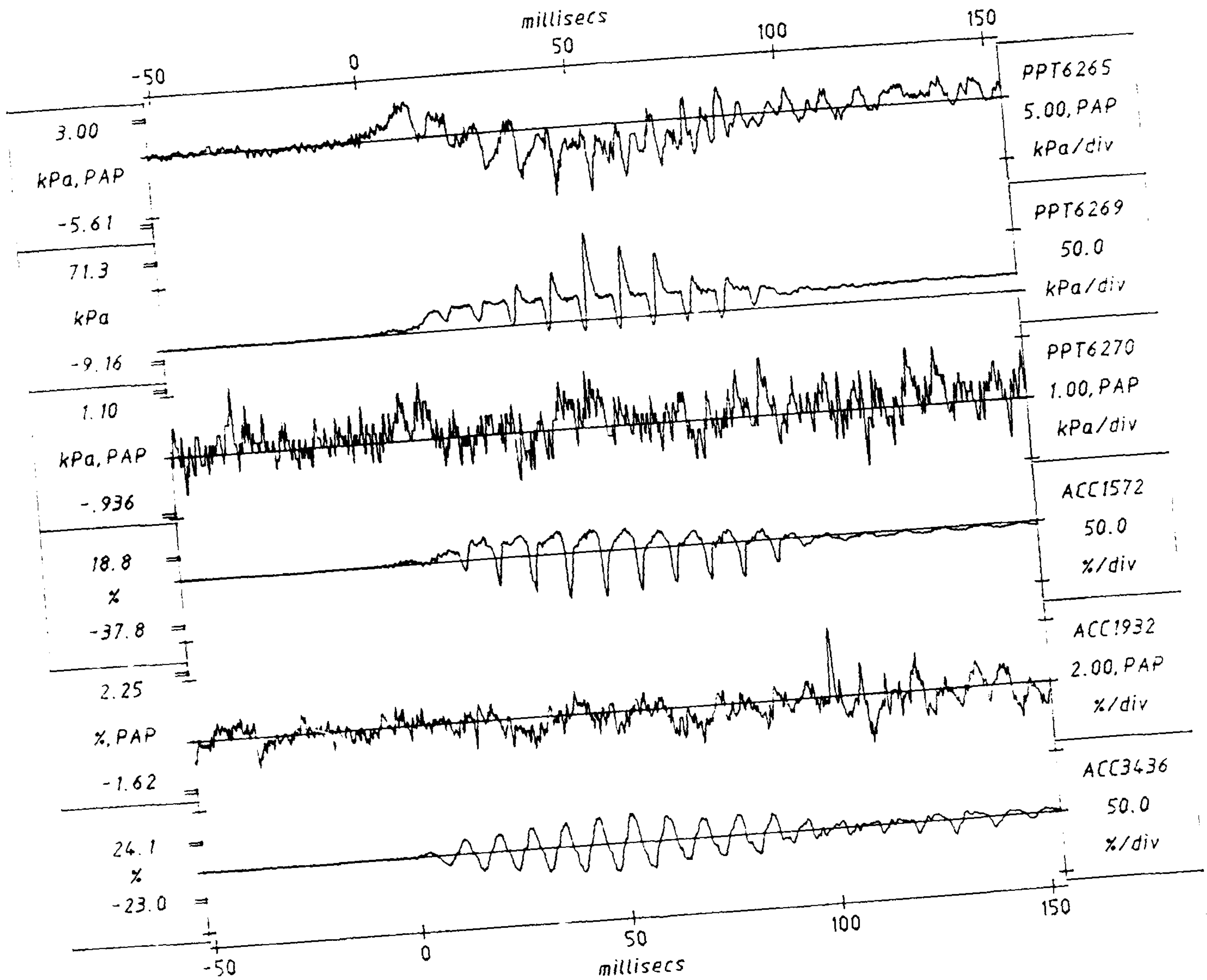


TEST GEM-5 MODEL LDO FLIGHT 1	EQ1	LONG-TERM TIME RECORDS	G = 80.0g Km = 11.6% Kp = 12.3%	FIG. NO. 13.4



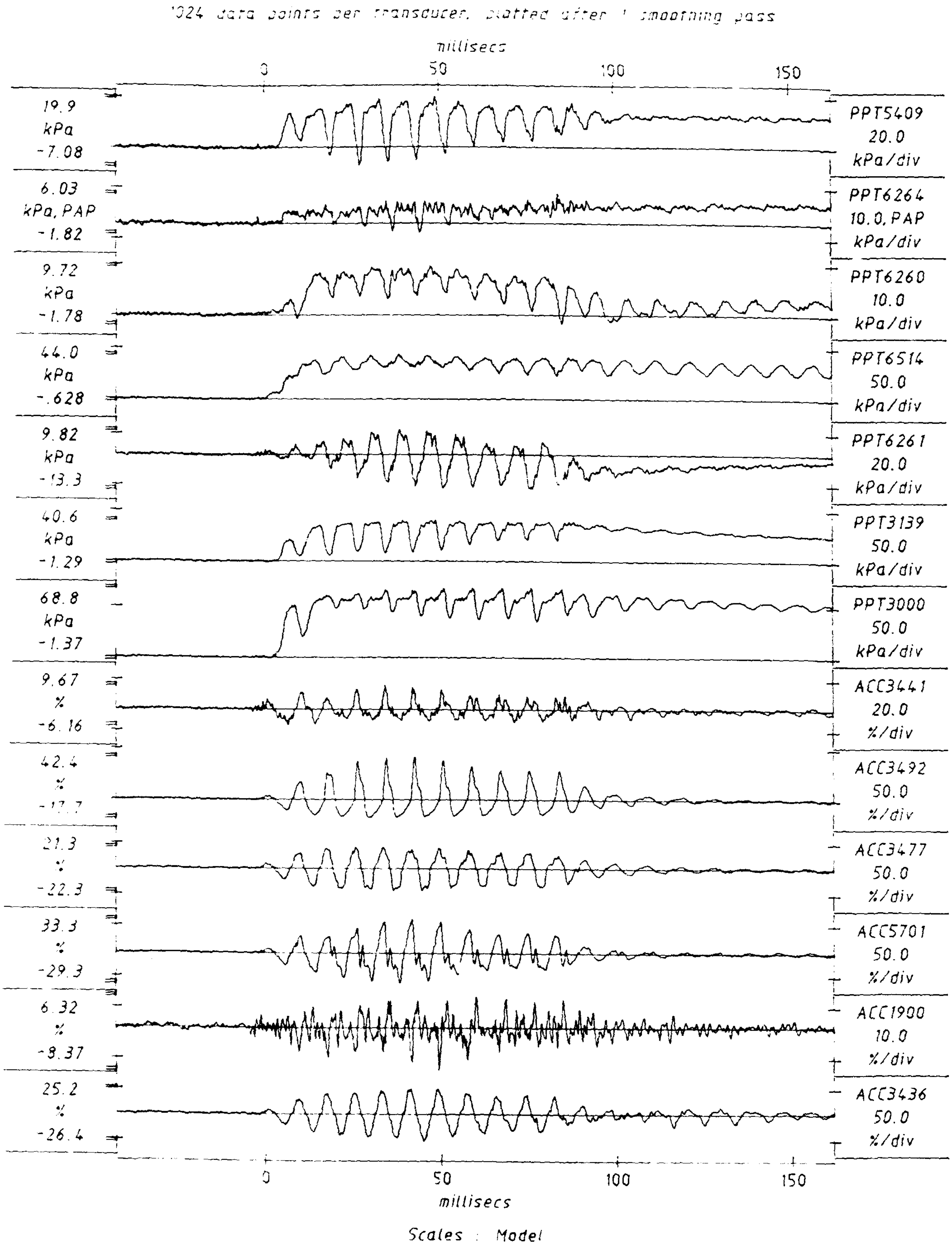
TEST GEM-5 MODEL LDO FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 23.2% Kp = 23.4%	FIG. NO. **13.5**

1024 data points per transducer, plotted after 1 smoothing pass



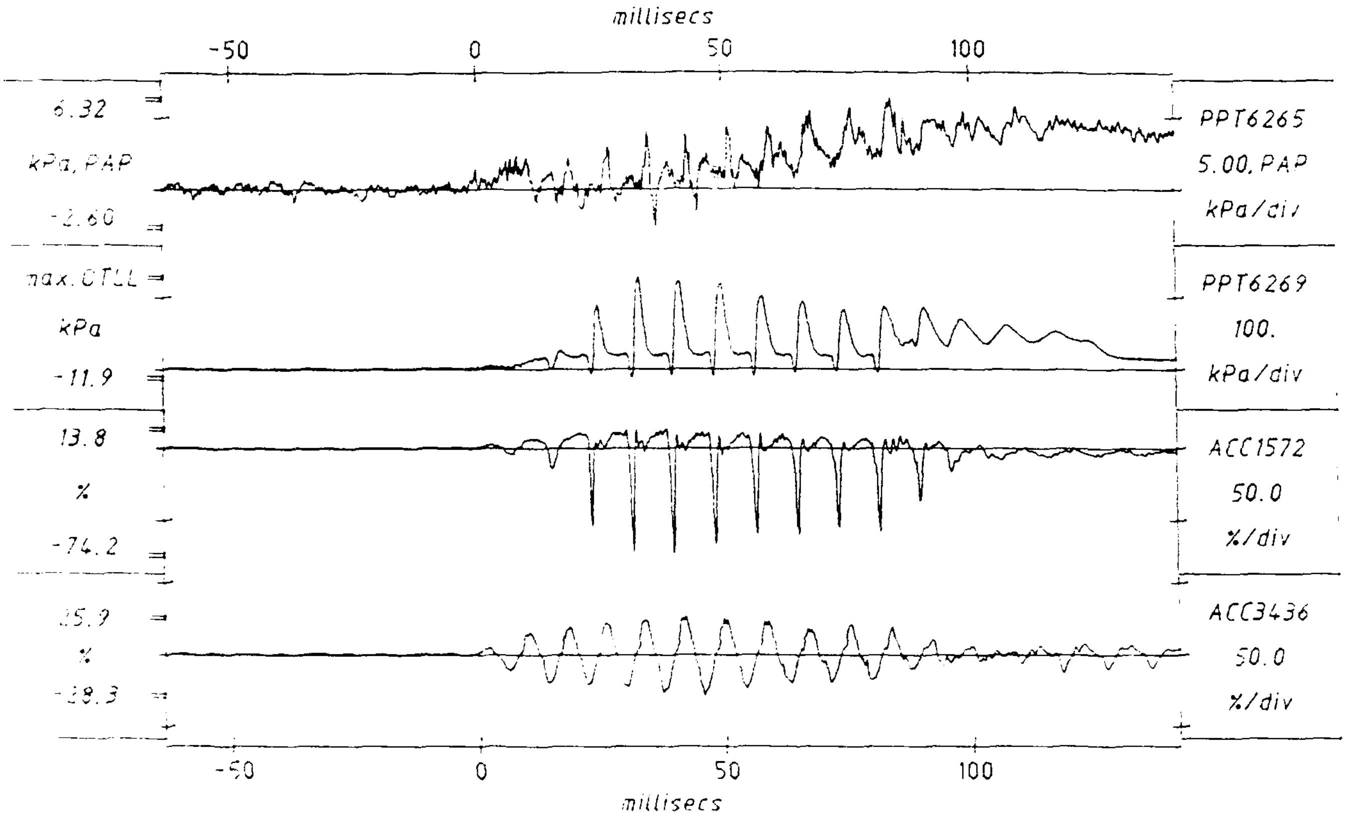
Scales : Model

TEST GEM-5 MODEL LDO FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 23.5% Kp = 24.1%	FIG. NO. 13.6



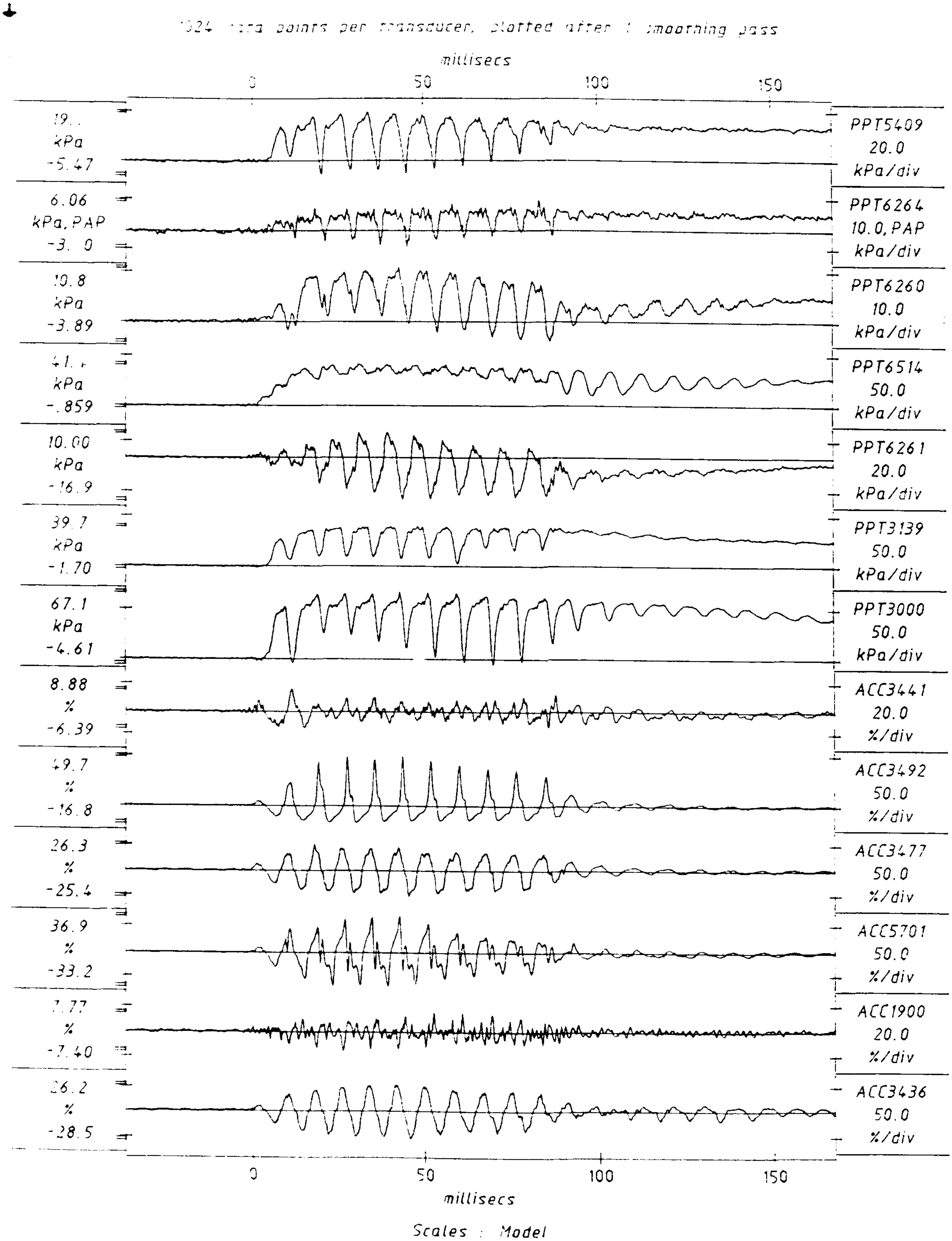
TEST GEM-5 MODEL 1DO FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 25.8% Kp = 26.4%	FIG. NO. 13.7

1024 data points per transducer, plotted after 1 smoothing pass



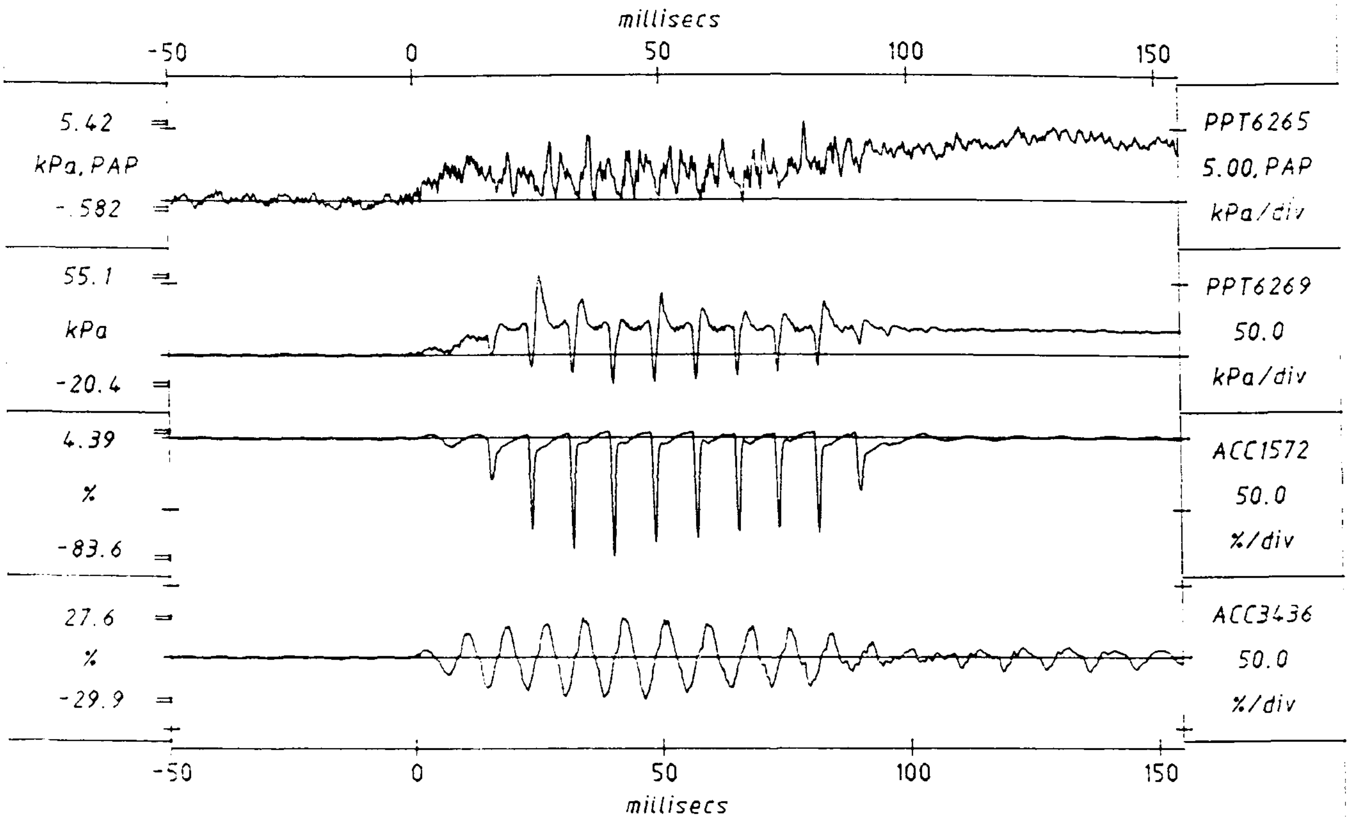
Scales : Model

TEST GEM-5 MODEL LDO FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 27.1% Kp = 28.3%	FIG. NO. 13.8



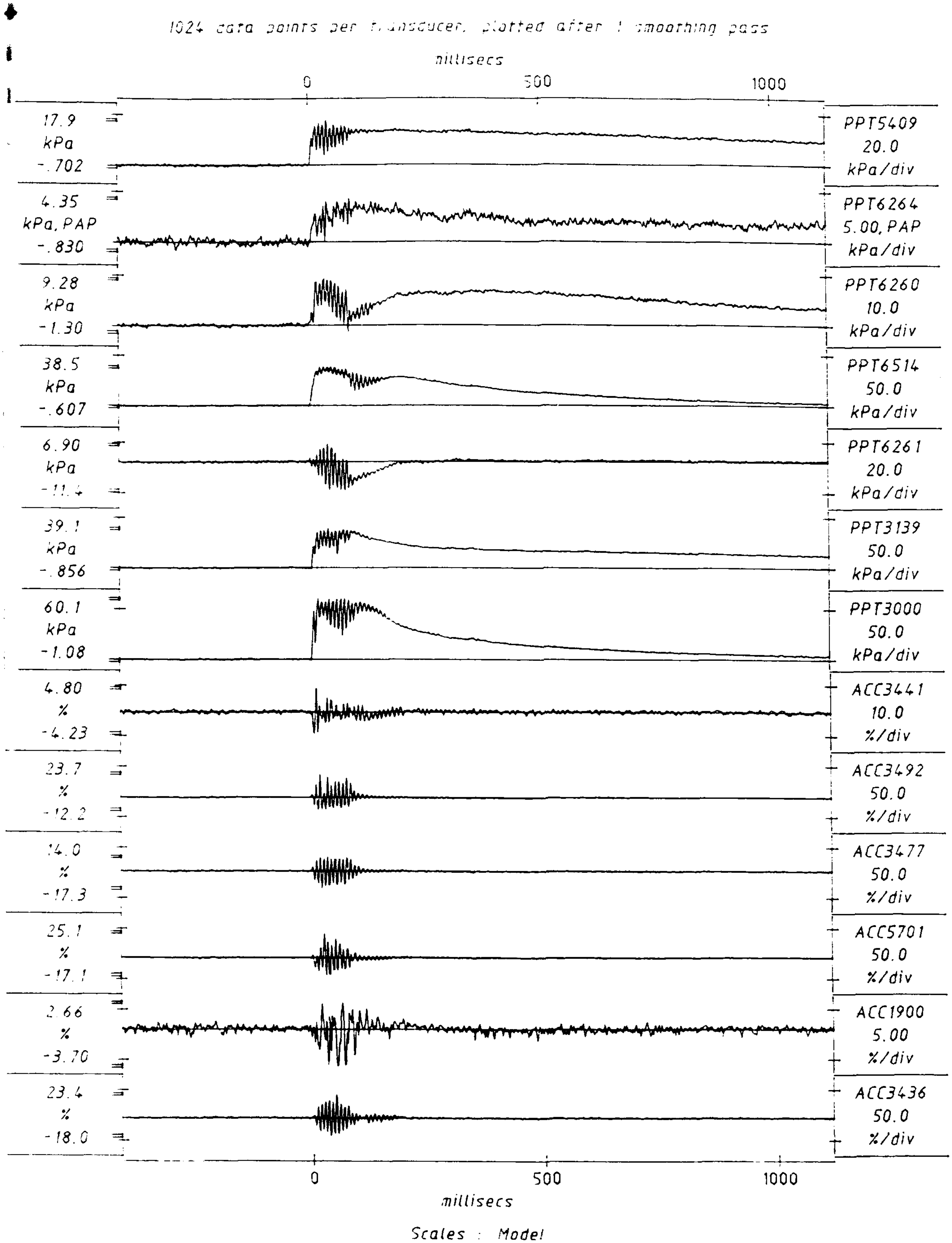
TEST GEM-5 MODEL LDO FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 27.3% Kp = 28.5%	FIG. NO. 13.9

1024 data points per transducer, plotted after 1 smoothing pass

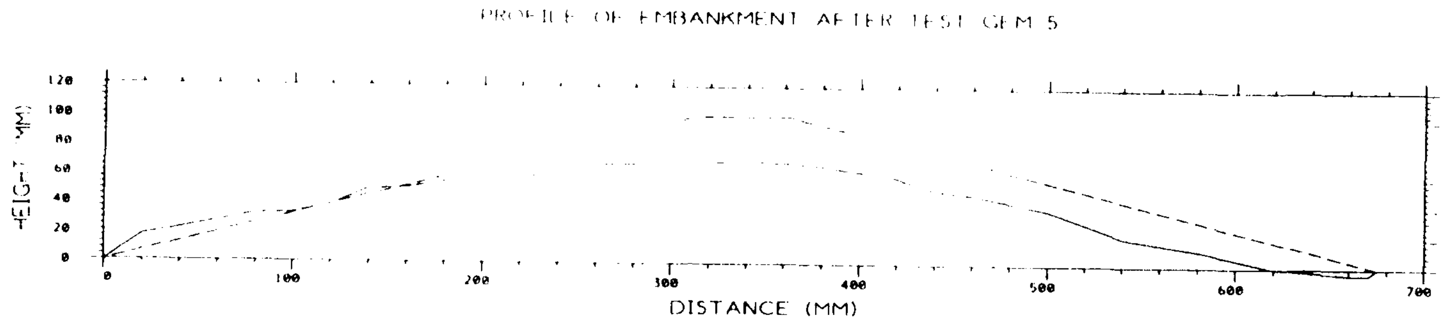


Scales : Model

TEST GEM-5 MODEL LDO FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 28.8% Kp = 29.9%	FIG. NO. 13.10



TEST GEM-5 MODEL LDO EQ4 FLIGHT 1	LONG-TERM TIME RECORDS	G = 80.0g Km = 20.7% Kp = 23.4%	FIG. NO. 13.11



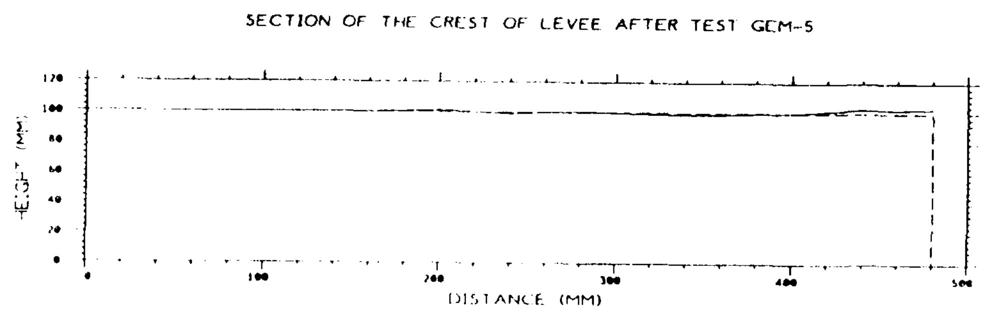


Fig.13.12 Post test longitudinal and sectional profile of model GEM-5

GEM - 6

14 Centrifuge test GEM-6

14.1 Configuration of the test

A schematic section of the centrifuge model GEM-6 is presented in Fig.14.1a. The location of the transducers is indicated in Fig.14.1b. In this test the loose pocket had a quadrilateral cross section as indicated in Fig.14.1a with a thickness of 40 mm and was 300 mm long. The loose section was placed along the width of the strong box and was 480 mm wide. The silicone oil with a viscosity of 80 cS was used as pore fluid and the level of the oil sea was kept plush with the crest of the levee.

14.2 Construction of the model

The dense section to the left and right of the loose pocket of sand shown in Fig.14.1a was constructed by raining of LB 52/100 sand through a sand hopper. Former plates were fixed in position using paper wedges. Latex rubber sheets were placed on the left hand side of the loose pocket to prevent the dissipation of excess pore pressure. At the end of phase I of construction described in section 4.0 thin Lasagne sheets which were softened by saturation were placed on the upper surface of the loose pocket of sand (see Fig.14.1a). Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was carried out as described earlier. Instruments were placed carefully at the required levels during the construction of the embankment and final saturation was carried out after Phase II construction was completed.

14.3 Test data

Four earthquakes were fired on this model. The box acceleration was recorded by ACC 3436. The strength of the earthquake was increased from 12.0 % in the first earthquake to 22.6 % in the fourth earthquake. Large excess pore pressures were generated within the model levee and are recorded by various PPT's indicated in Fig.14.1b. The centrifuge test data is presented in Figs. 14.2 to 14.11. Long term records for all the transducers during and after earthquake 4 are presented in Figs.14.10 and 14.11. After the centrifuge test the final profile of the levee was measured and post test investigations were conducted. The final profile of the levee after the test is presented if Fig.14.12.

Plate 14.1 Slipping of levee slope in test GEM-6

Plate 14.2 Dense sand overlaying loose portion
(observe change of color of sand on left hand edge)

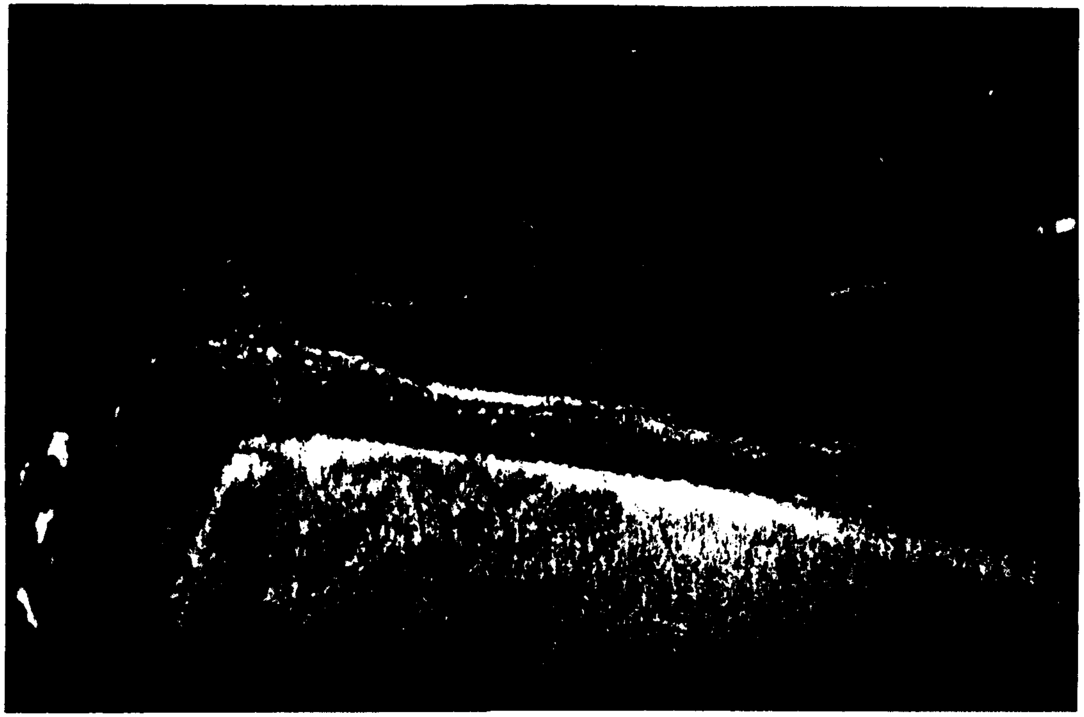
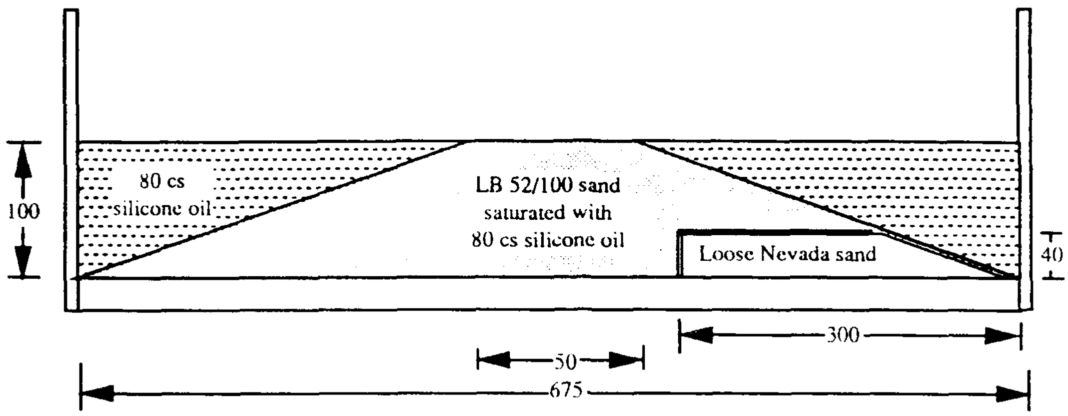
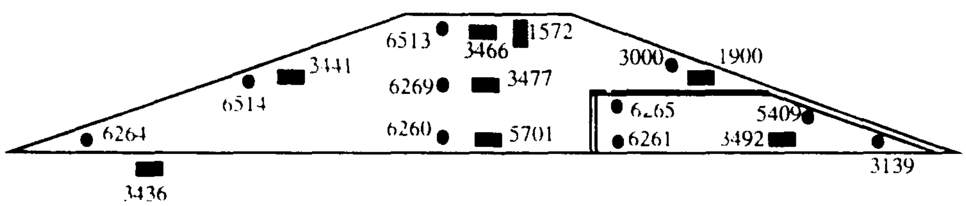


Plate 14.3 Section through centrifuge model GEM-6
(observe the settlement of right hand edge of loose section
and increase in left hand dimension)

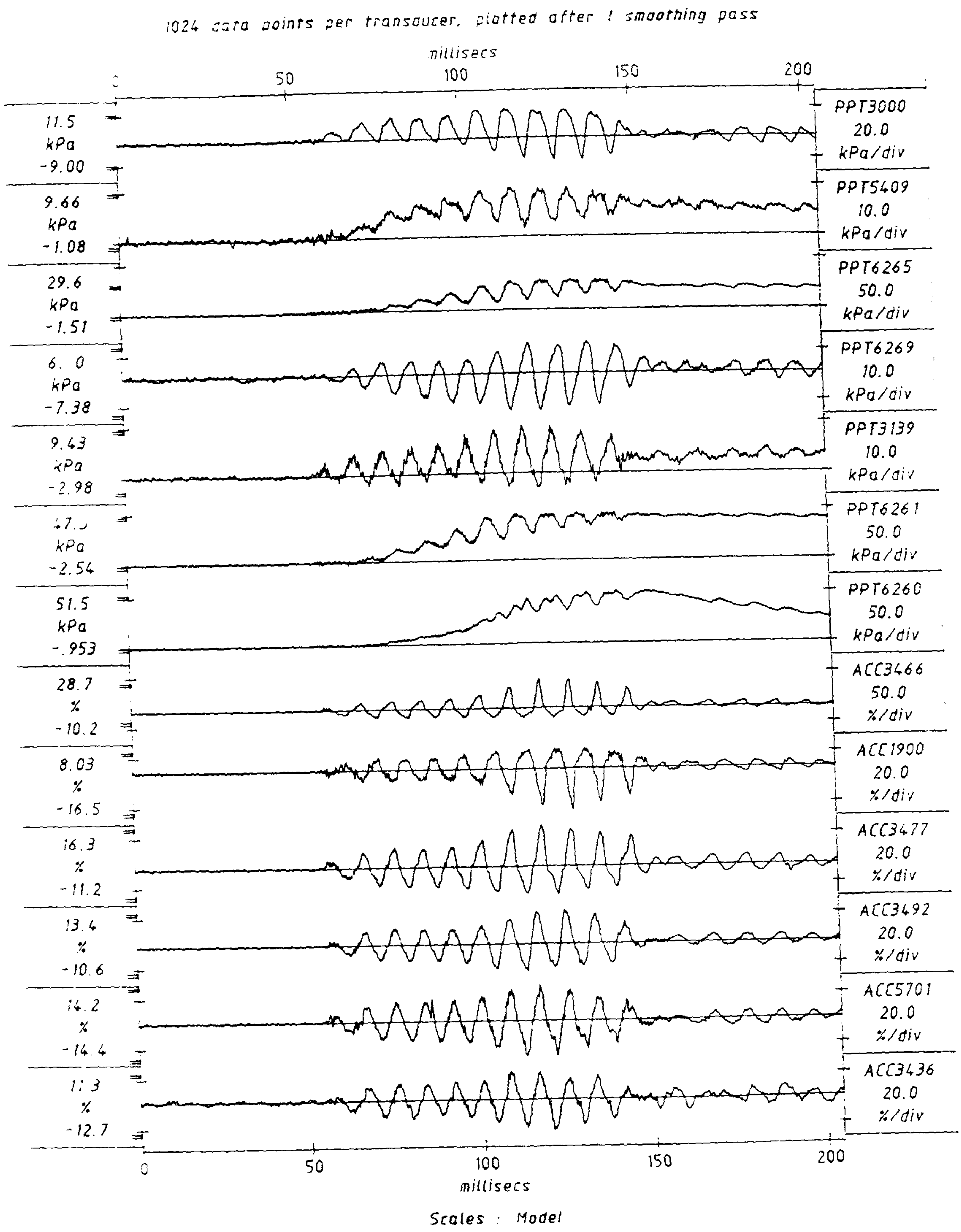


A) Schematic section of centrifuge model GEM-6



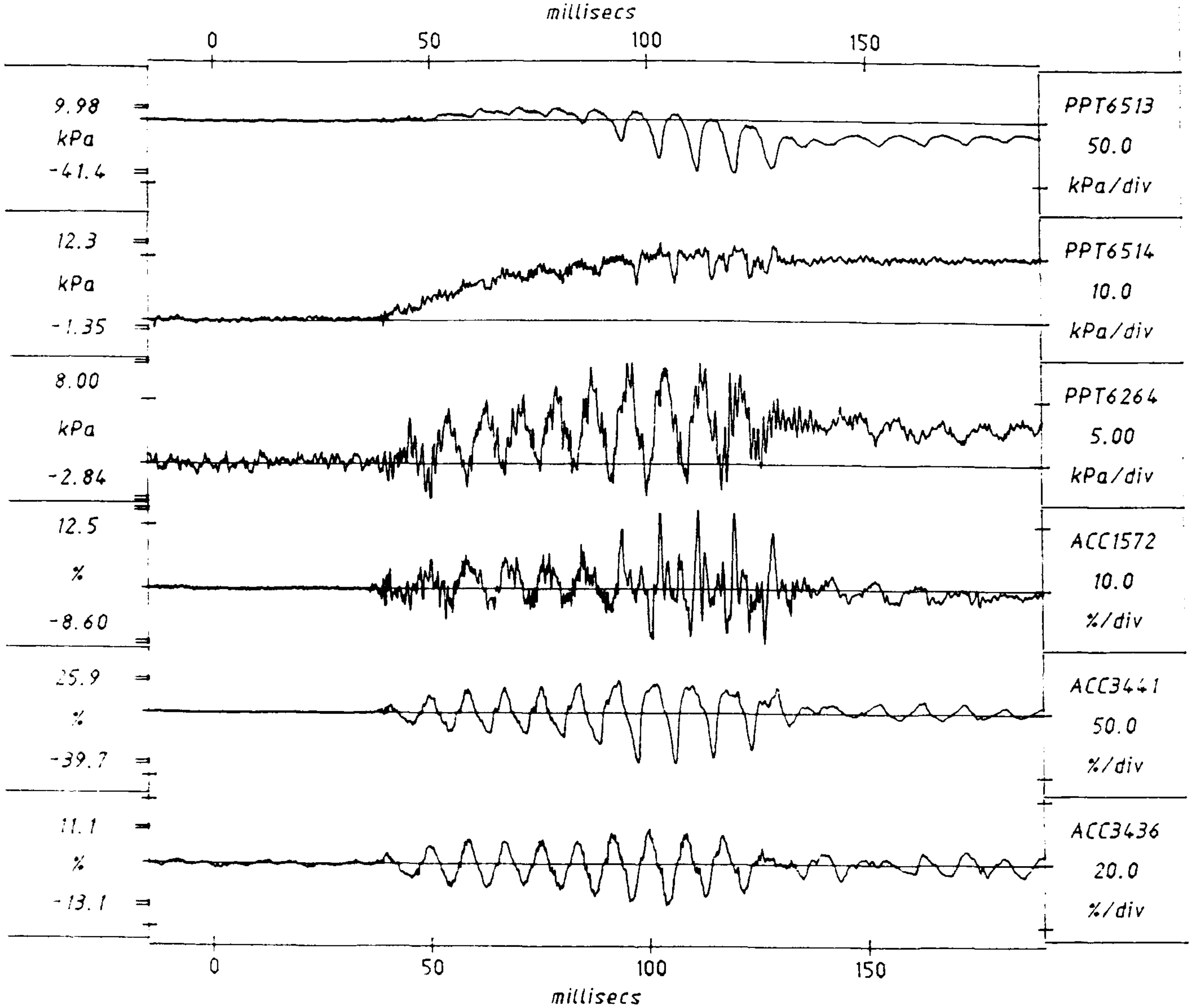
B) Placement of transducers in centrifuge test GEM-6

FIG. 14.1



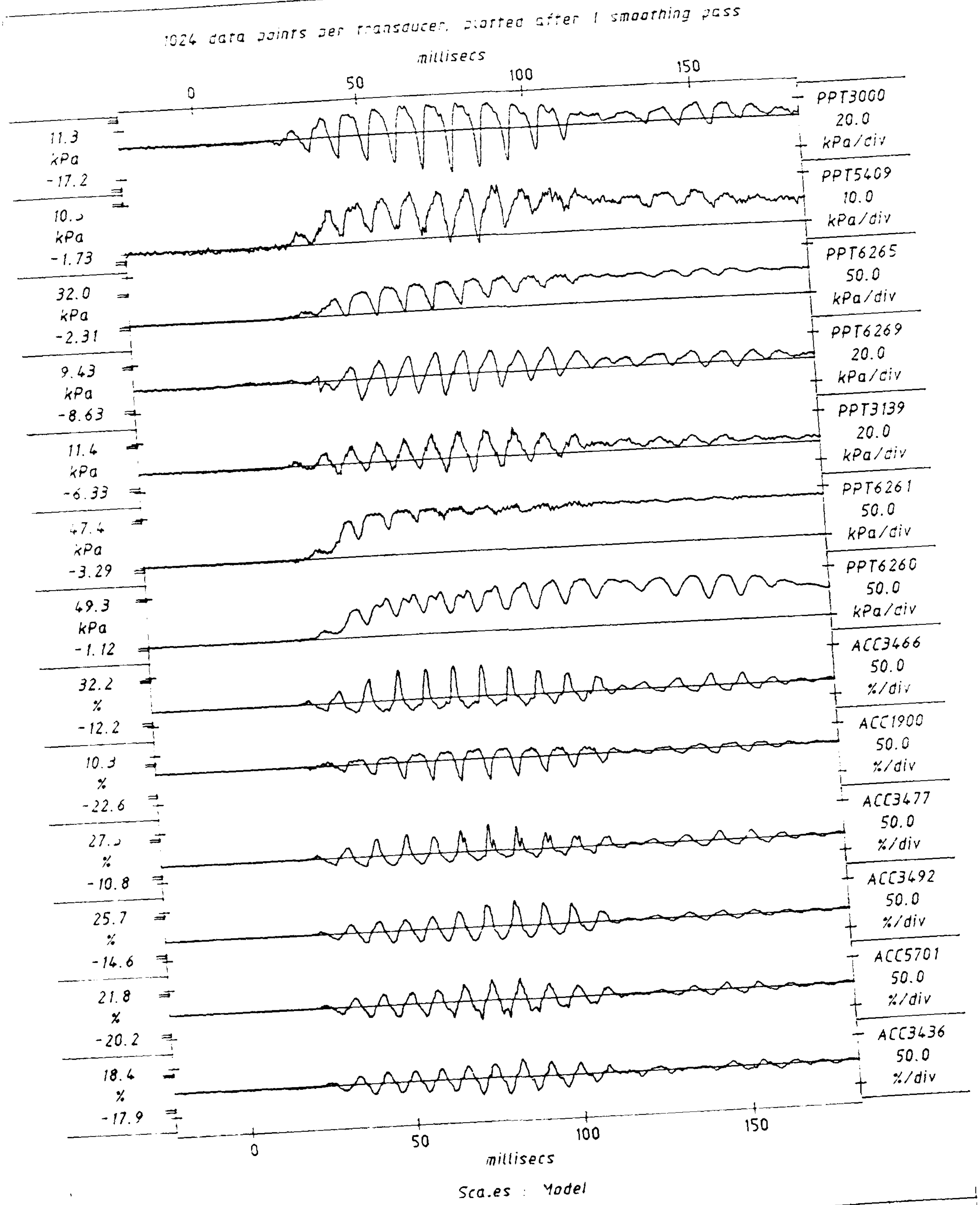
TEST GEM-6 MODEL LDO EQ1 FLIGHT 1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 12.0% Kp = 12.7%	FIG. NO. 14.2

1024 data points per transducer, plotted after 1 smoothing pass



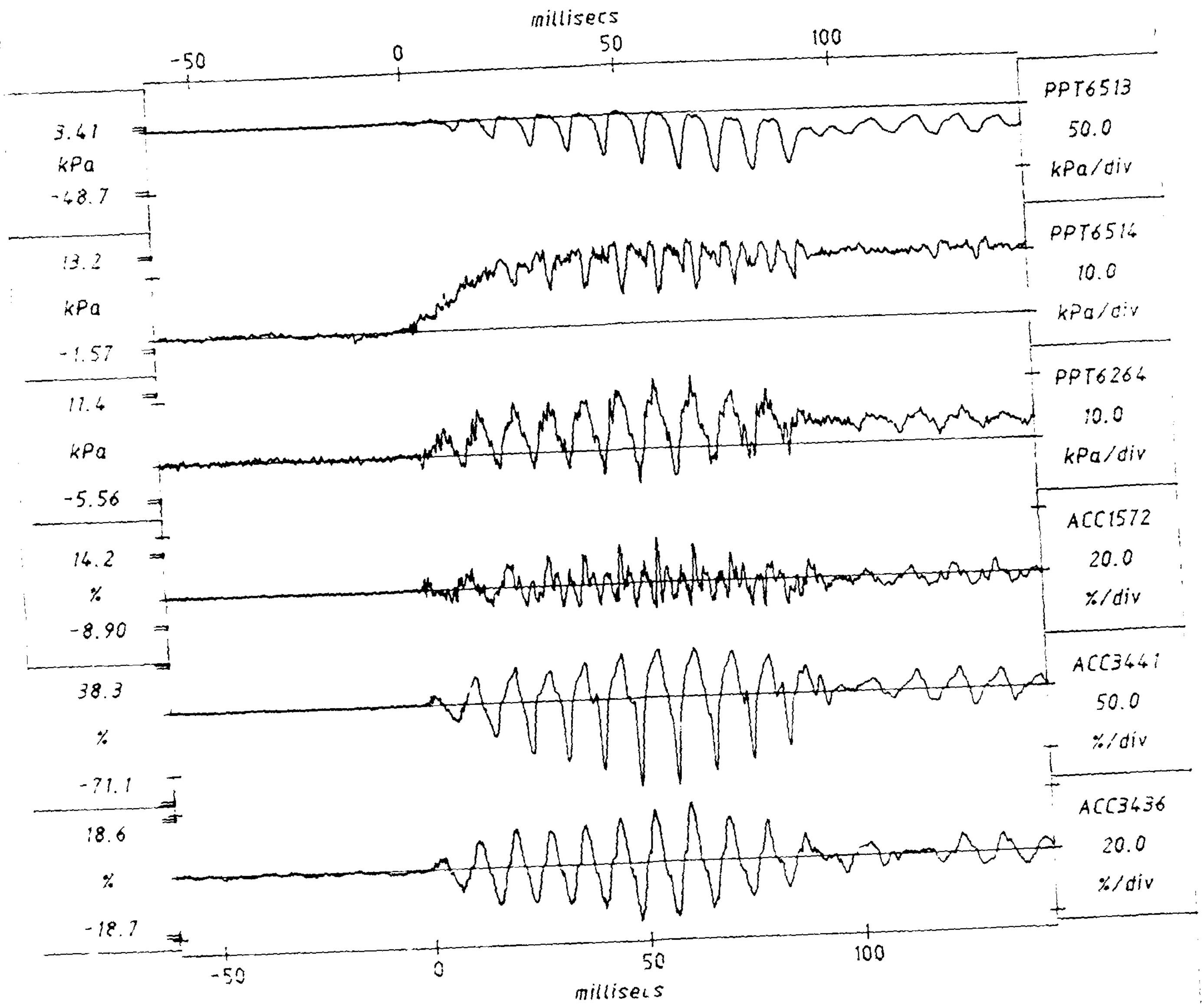
Scales : Model

TEST GEM-6 MODEL LDO FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 80.0g Km = 12.1% Kp = 13.1%	FIG. NO. 14.3



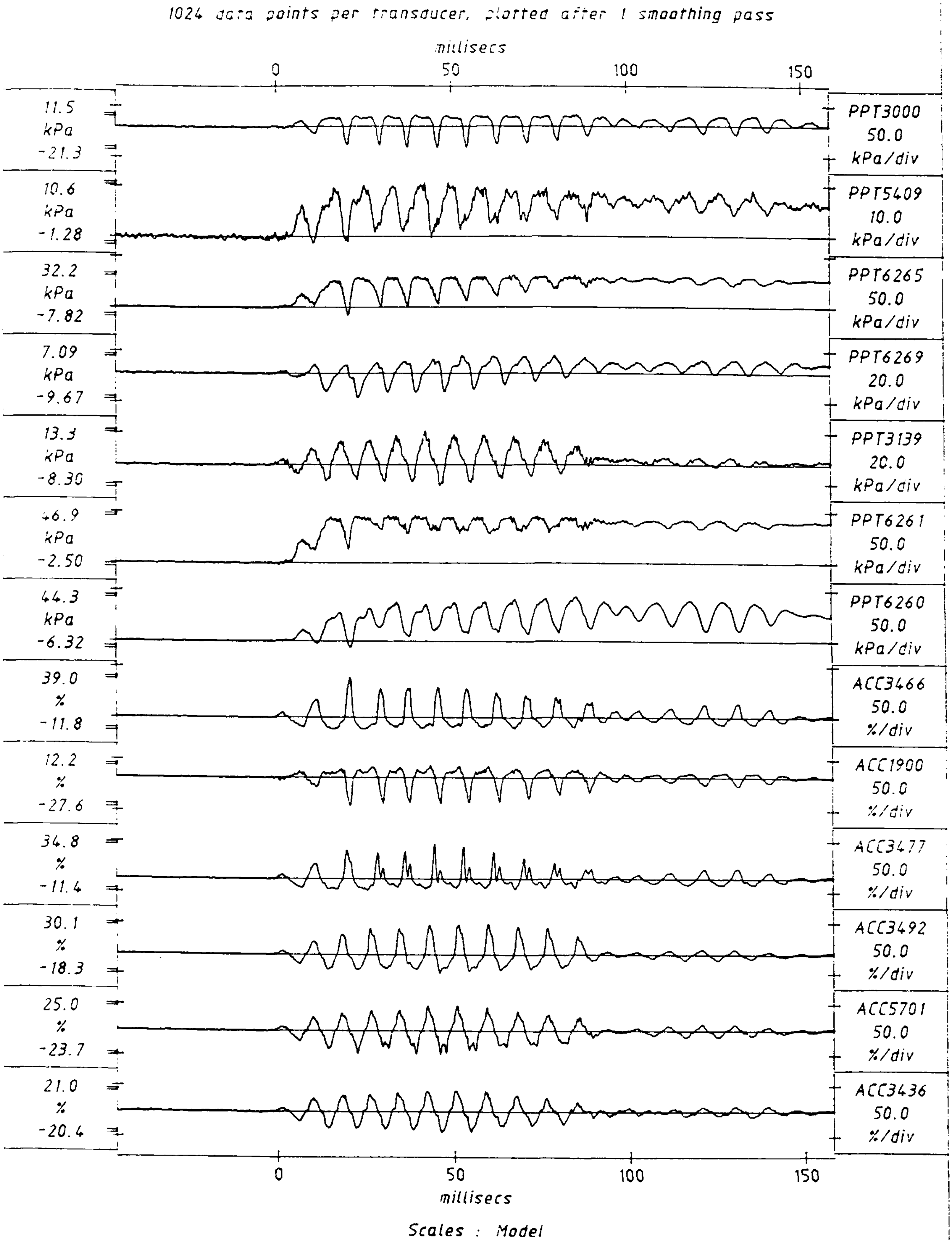
TEST GEM-6 MODEL LDO FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 18.1% Kp = 18.4%	FIG. NO. 14.4

1024 data points per transducer, plotted after 1 smoothing pass



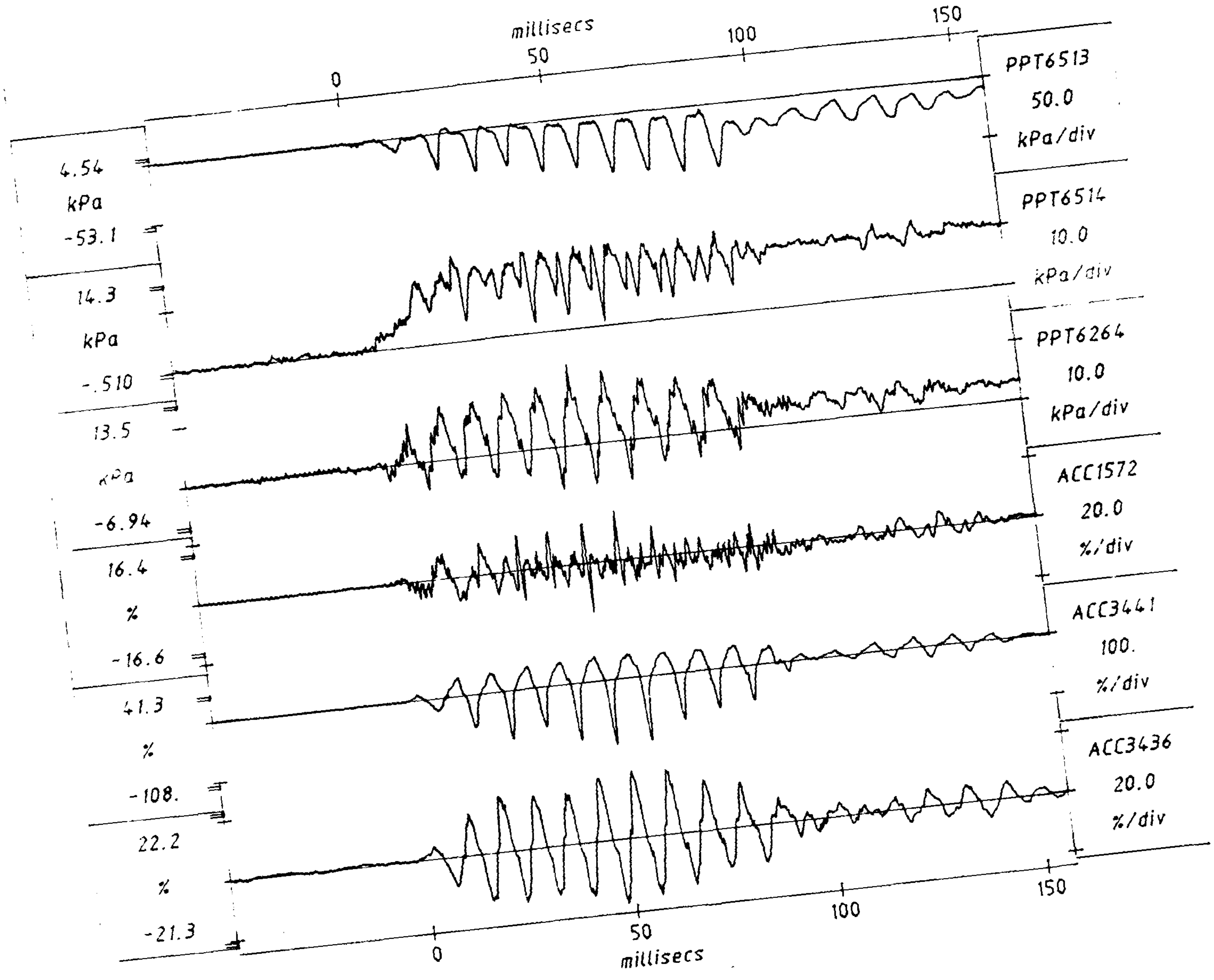
Scales : Model

TEST GEM-6 MODEL LDO FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 80.0g Km = 18.7% Kp = 18.7%	FIG. NO. 14.5



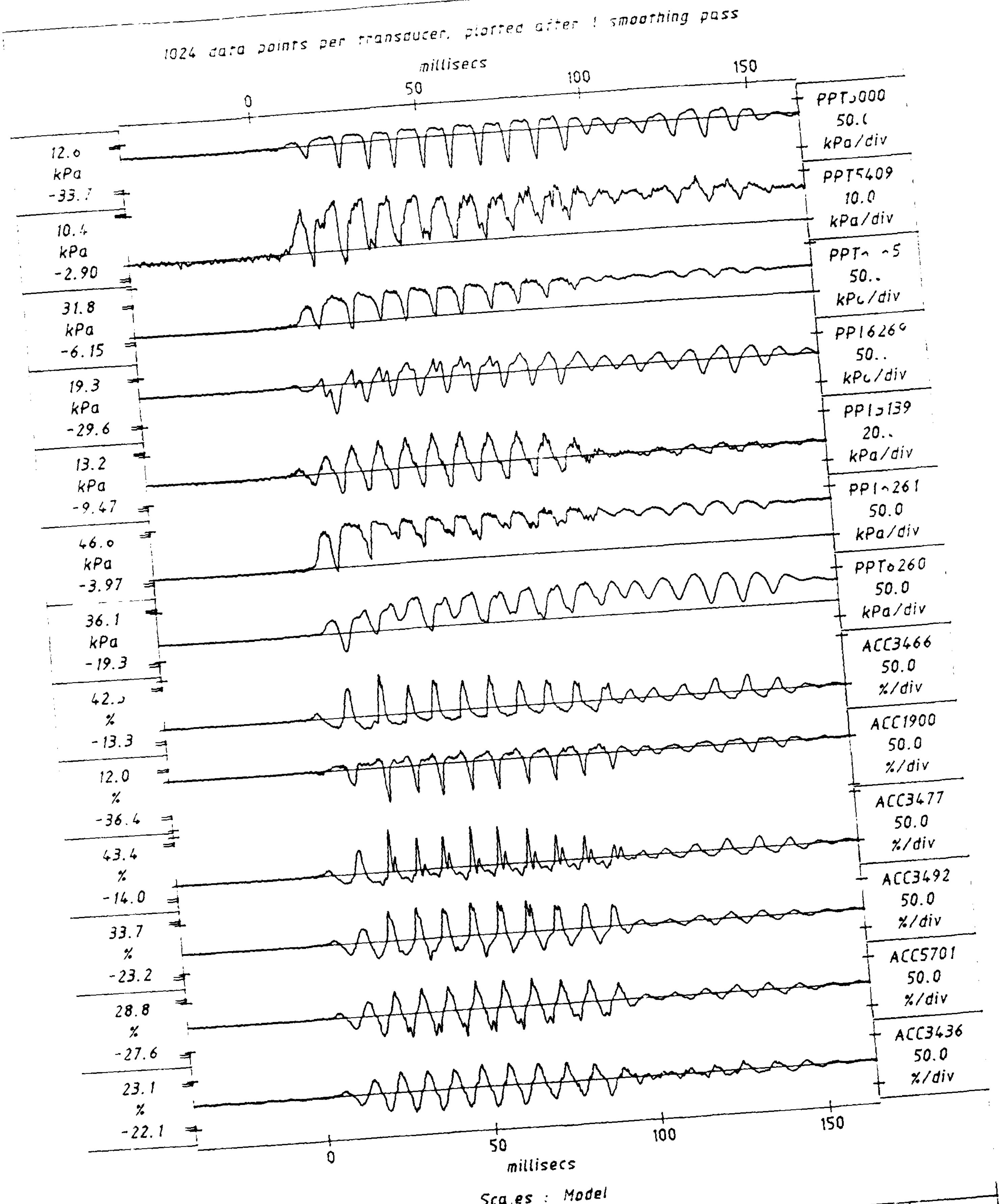
TEST GEM-6 MODEL LDO FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 20.7% Kp = 21.0%	FIG. NO. 14.6

1024 data points per transducer, plotted after 1 smoothing pass



Scales : Model

TEST GEM-6 MODEL LDO FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 80.0g Km = 21.7% Kp = 22.2%	FIG. NO. 14.7



TEST GEM-6
MODEL LDO
FLIGHT 1

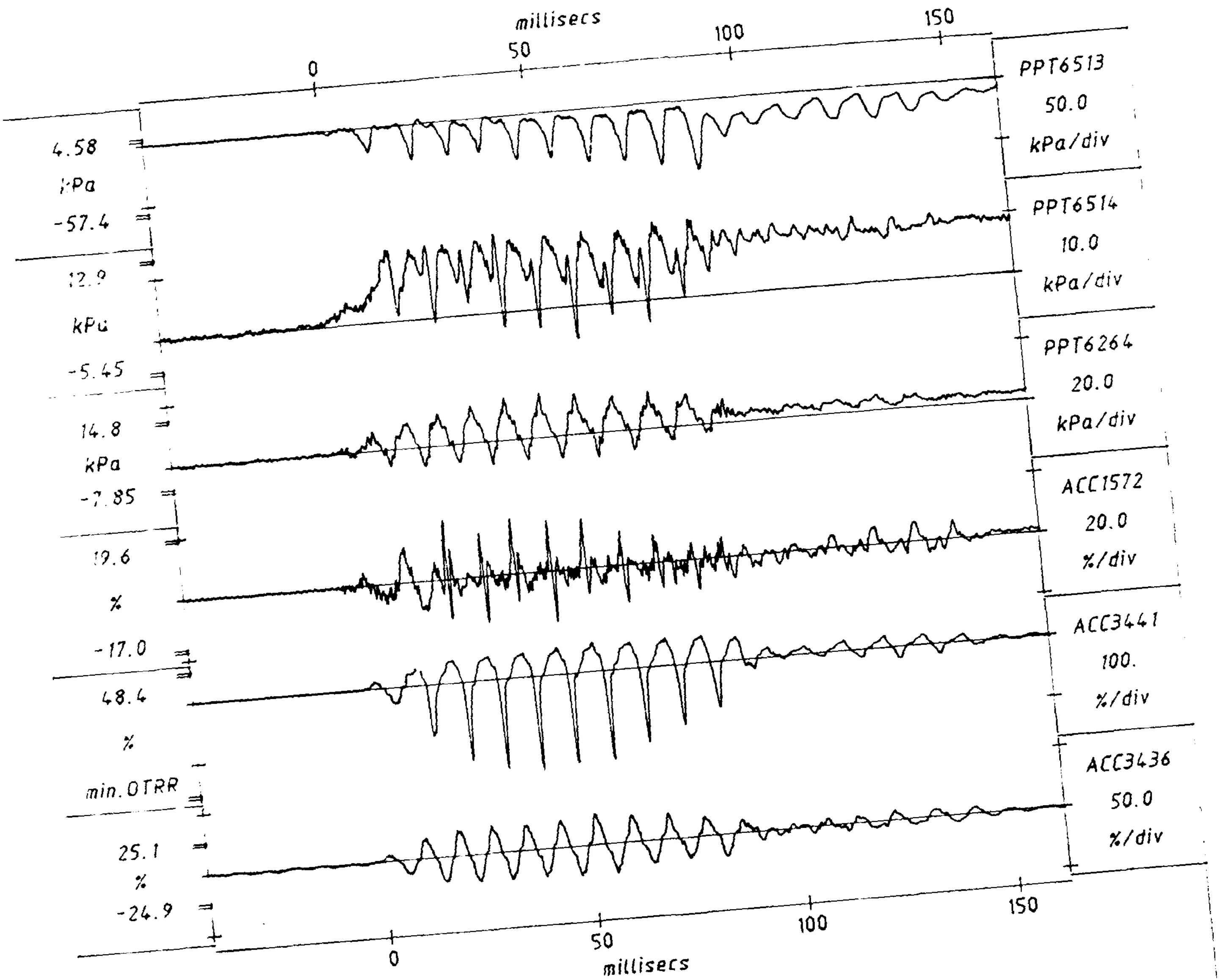
EQ4

SHORT-TERM
TIME RECORDS

G = 80.0g
Km = 22.6%
Kp = 23.1%

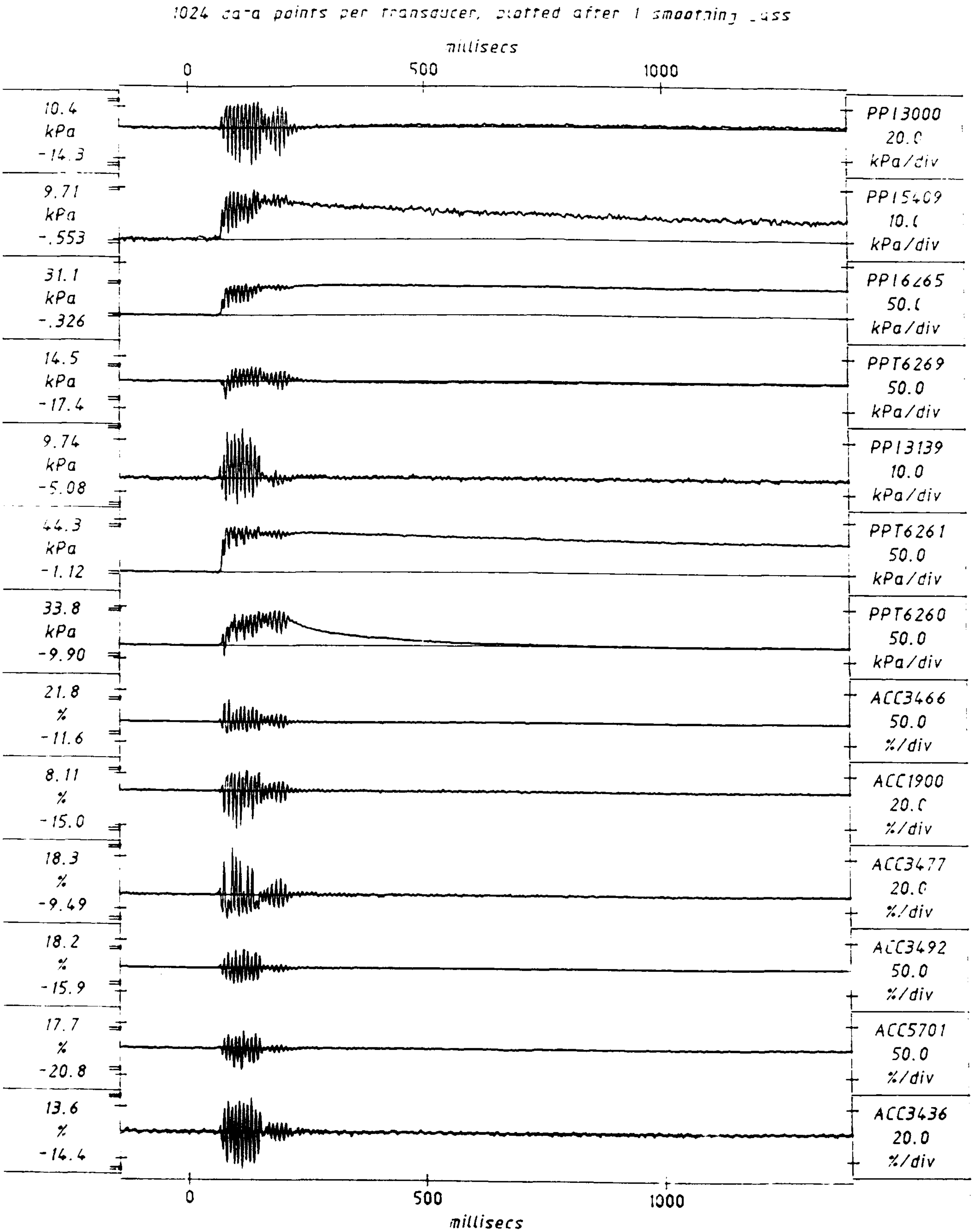
FIG. NO.
14.8

1024 da-a points per transducer, plotted after 1 smoothing pass



Scales : Model

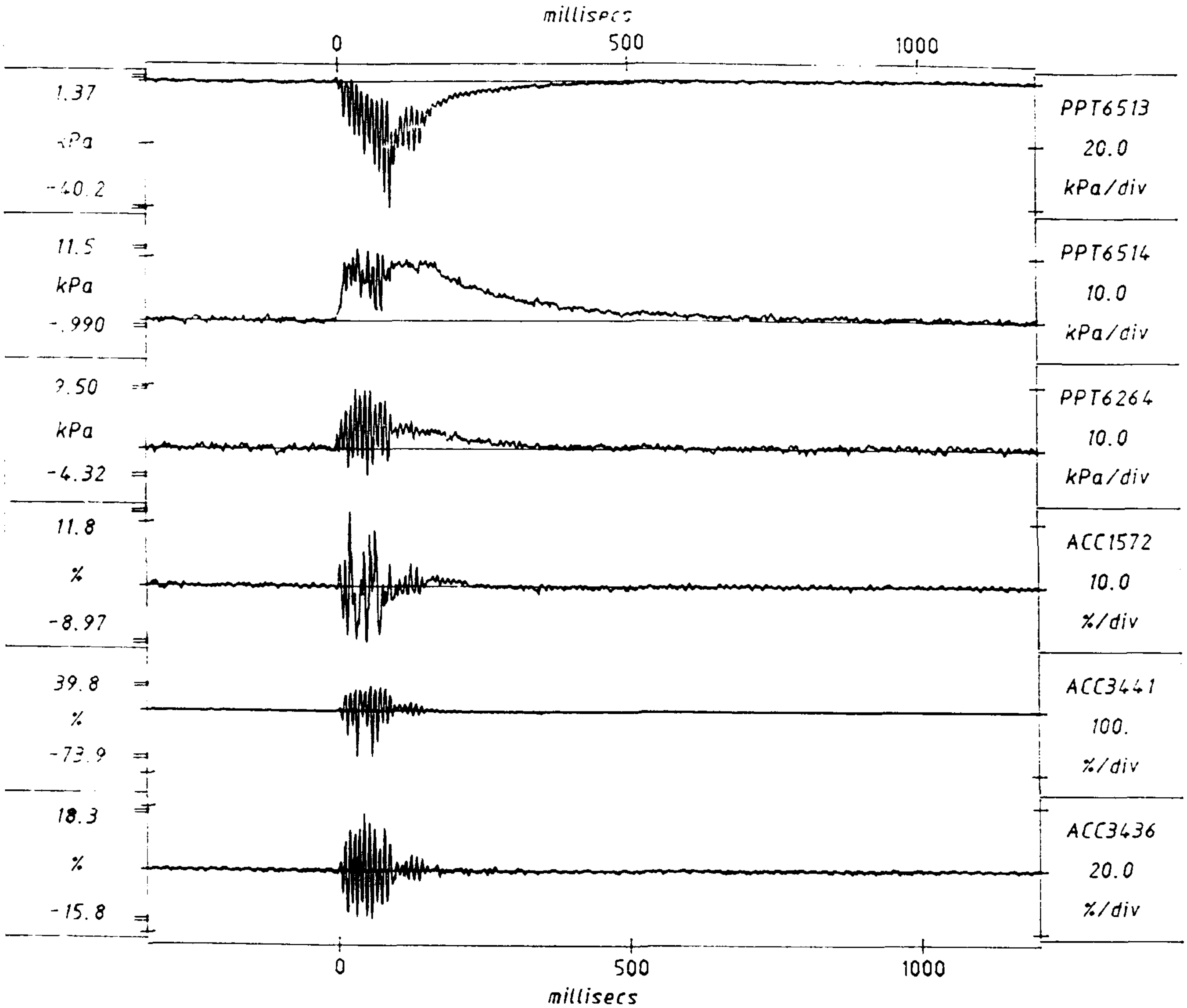
TEST GEM-6 MODEL LDO FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 80.0g Km = 25.0% Kp = 25.1%	FIG. NO. 14.9



Scales : More.

TEST GEM-6 MODEL LDO FLIGHT 1	EQ4	LONG-TERM TIME RECORDS	G = 80.0g Km = 14.0% Kp = 14.4%	FIG. NO. 14.10

1024 data points per transducer, plotted after 1 smoothing pass



Scales : Model

TEST GEM-6 MODEL LDO FLIGHT 1	EQ4	LONG-TERM TIME RECORDS	G = 80.0g Km = 17.1% Kp = 18.3%	FIG. NO. 14.11

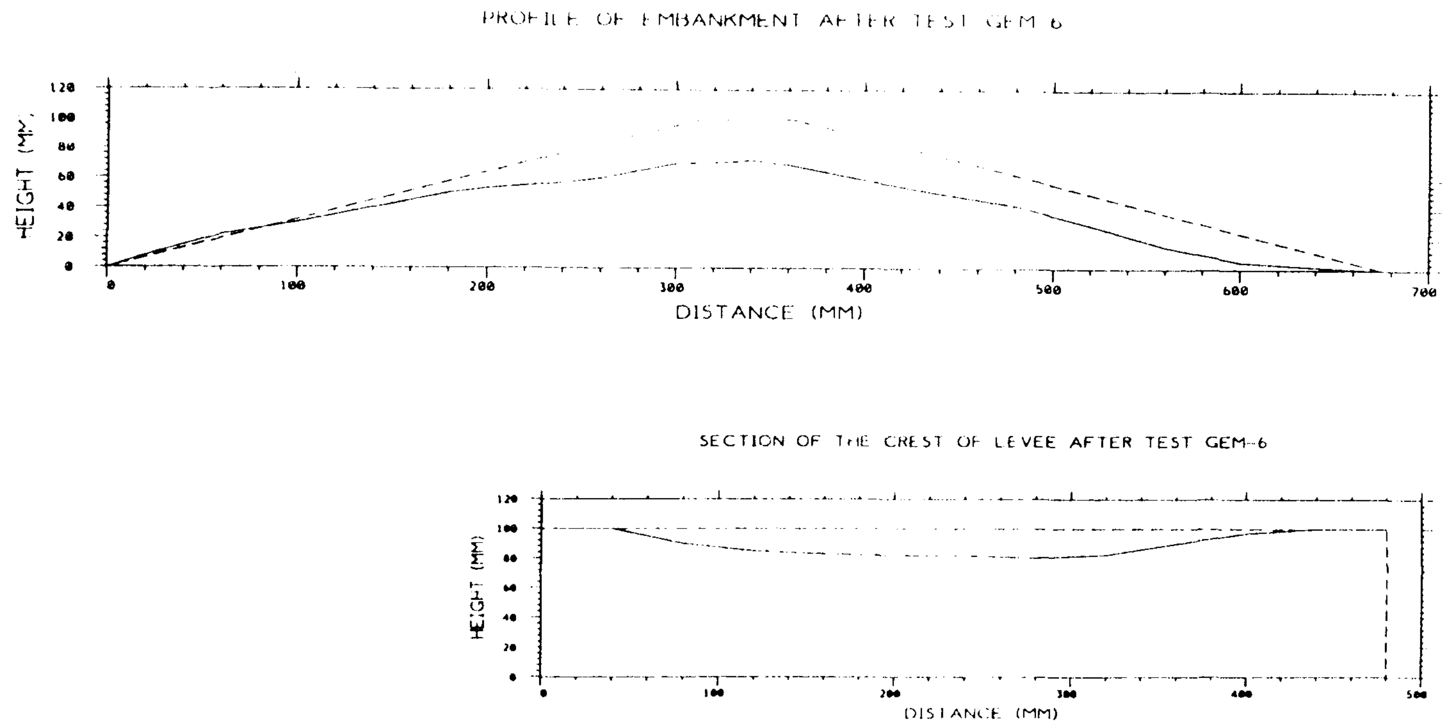


Fig.14.12 Post test longitudinal and sectional profile of model GEM-6

15 Conclusions

Dynamic centrifuge modelling of an embankment with a loose pocket of sand enclosed within the embankment was carried out. Two centrifuge tests were conducted using freezing techniques to maintain the loose fabric of the pocket of sand which was defrosted after loading the model on to the centrifuge arm. The model preparation techniques were found to be satisfactory. A draw down was achieved in the centrifuge test GEM-2 by extracting the water from the downstream side of the levee during the flight using a pnuematically operated valve before any earthquake was fired. The results from these tests were found to be satisfactory. However, the excess pore pressures generated during the earthquakes were dissipated rapidly as water was used as pore fluid.

Two control tests were conducted to investigate the settlement of the loose pocket of sand when high viscous silicone oil was used as pore fluid. Impermeable Lasagne sheets were placed to enclose the loose pocket in the embankment. The results indicated that by careful transport of the centrifuge model on to the arm and maintaining the suction pressure of -30 cm of mercury during this phase the settlement of the loose pocket could be limited to a very small magnitude.

Four dynamic centrifuge tests were conducted using silicone oil as the model pore fluid. In each of these centrifuge tests the geometry of the loose pocket of sand was changed. The embankment slope suffered a slip during the earthquake in these tests. The slip occured predominantly on the side of the levee where the loose pocket of sand was present. Liquefaction of the loose section resulted in the slip of the slope. The data obtained during these tests is presented in this report together with the post test profiles of the levee slopes. A more thorough analysis of the data recorded during these tests will be presented in a subsequent technical report.

Acknowledgements

The author wishes to express his deep gratitude for the technicians Chris Collison and Paul Ford for their active help in conducting the centrifuge tests. Neil Baker has provided excellent support on the instrumentation side of the centrifuge tests. Finally the guidance and help of Colin Smith in designing the Peltier heat pumps are gratefully acknowledged. Special thanks are due to Dr.Ryan Philips for providing overall guidance in conducting these tests.

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