Data Report Of Three Dynamic Centrifuge Model Test On Piles And Pile Groups

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PREFACE

This data report contains the data from three dynamic centrifuge test on pile foundations carried out by A. Maheetharan on the Cambridge Geotechnical Centrifuge (Schofield, 1981).

CONTENTS

1. Introduction

1.1. Background

This data report describes the centrifuge model test carried out (in Appril 1987) to study the earthquake response of piles and pile groups. Three test were conducted one with a single pile with a pile cap, one with a single pile without a pile cap and one with a group of four piles with a pile cap. The model construction and the experimental method are described briefly. The data obtained in these test are presented here. No analysis is included at this stage.

1.2. Centrifuge Modelling

In the geotechnical centrifuge modelling the prototype gravitational forces are simulated by centrifuge acceleration (N times the gravity). The earthquake accelerations are simulated by shaking the model during flight with the acceleration N times higher than that of the prototype in order to satisfy the dynamic similarity.

A detailed description for scaling requirements are discussed by Schofield(1981). The error induced by curvature of the stress field and the variation of gravity with the depth of the model were also discussed therein, and were considered to have a minimal effect in these test. The scaling laws are summarised in Table 1.

1.3. Outline of the Report

The report is organised as follows. Chapter two describes the equipment and the instrumentation. The detail of model construction and the experimental procedure are given in the next chapter. The fourth chapter deals with the presentation of data. The soil, pile properties are summarised in the appendix.

2. Equipment and Instrumentation

2.1. Cambridge Geotechnical Centrifuge

The test described in this report were carried out on the Cambridge Geotechnical Centrifuge. A detailed description of the above centrifuge is given by Schofield (1981). The working radius of the centrifuge is 4m and the maximum allowable speed is 186 rpm, at which the acceleration at 4m radius is 155g. Normally the highest authorised acceleration for dynamic cases are 80g and the corresponding package weight is 287 kg. Data logging from the transducers is done by electrical slip rings. The swinging platform on the centrifuge arm allows for easily model construction.

2.2. Bumpy Road Earthquake Simulator

The Cambridge Geotechnical centrifuge bumpy road earthquake simulator (Fig 2.1) developed by Kutter (1982) was used to simulate the earthquake. Basically the apparatus operates by forcing a wheel on the centrifuge arm to follow a curved and profiled steel track which is attached to the wall of the centrifuge pit. These oscillations are transmitted through a lever mechanism to vibrate the soil model laterally. The track used in these test could input an earthquake with the frequency of 120.4 Hz at 80g. Each earthquake consist of 10 cycles and the duration is 100 milliseconds at 80g. This corresponds to the prototype earthquake of 8 seconds duration.

The amplitude of the input earthquake could be varied during flight using the slider offset mechanism. The maximum allowable input acceleration depends on the package weight and could be obtained from the experimentally obtained resonance curve. Because of the resonance of the arm the magnitude of the transmitted earthquake to the model is normally much higher than the selected input acceleration. Hence usually the results of the first earthquake in a sequence is used as a guide line to select the input acceleration for the subsequent test in that sequence.

2.3. Instrumentation

2.3.1. Linear Variable Displacement Transformers (LVDT's)

Direct current linear variable displacement transformers (LVDT) manufactured by Sangamo were used to measure the static and dynamic displacements. In all test a sensitive short type model which has a range of 5mm was used with the supply voltage of 10 V DC. Their dynamic response at high frequency is very poor with respect to magnitude and phase.

2.3.2. Accelerometers

Miniature piezo-electric accelerometers, type A/23 and A/25/E (by D. J. Bitchall Ltd, Milden Hall) were used to measure the earthquake acceleration at various points in the model. Some accelerometers (type A/23) were placed at various position in the soil and on the pile cap. An accelerometer (type A/25/E) was also attached to the pile tip to measure the transmitted soil acceleration. Their frequency response is flat from 10 Hz to 16 kHz, and hence would follow the soil acceleration accurately. The accuracy of these acceleration depends on the calibrating system and it is about $\pm 5\%$. A typical calibration is about 0.25 V/g .

These accelerometers were calibrated before model construction using the same cable as used in the test, to avoid the variation in calibration constant due to its length and type.

2.3.3. Strain Gauges

Tinsley 3/120/P/C-23 type miniature, linear foil strain gauge (Tinsley Telcon Ltd.) were used to instrument the piles used for test AM-1 and AM-2. Tinsley 35/350EC23 type miniature, linear foil strain gauges were used to instrument the piles used for test AM-3. These piles were instrumented externally to measure the dynamically induced bending moments along the pile. A full bridge circuit was used. The distribution of strain gauges are shown in fig 2.2. These strain gauges were protected by shrink fit tubing.

The model piles were made of 15SWG dural tubing with the external and internal diameter of 9.525mm and 3.175 mm respectively. These piles were calibrated by supporting the piles at knife edges and by applying loads at the mid span. The supply voltage used for the strain gauges was 5V.

2.3.4. Data Acquisition

All transducers were plugged into the junction boxes attached to the centrifuge arm. These signals were amplified in the junction box depending on the requirements and were taken to the bank of amplifiers in the console room through slip rings. In the console room the amplifications were adjusted again where necessary. Transducer readings were recorded, during swing up and, before and after earthquakes. However in order to record the dynamic events such as earthquake (lasting approximately for 0.1 seconds) two high speed Racal Analogue tape recorders were used. Fourteen channels could be recorded simultaneously and subsequently digitised using a Automotion 32K Alpha mini computer. These digitised data can then be stored on the floppy discs for subsequent analysis, processing and plotting.

3. Model Construction And Experimental Procedure

3.1. Convention for Labelling test

Three test were carried out which are named AM-1, AM-2 and AM-3. Several earthquakes were imposed on each model and each of one is identified by its earthquake number. For instance the second earthquakes imposed on model AM-3 will be referred as AM-3 EQ-2.

3.2. Definition of the co-ordinate system

Fig 3.1 shows a plan and elevation of the Bumpy road strong box swinging container use for the test. The positive X, Y and Z axis which were used to define the positions of transducers are shown in these figures. The dimensions of the model sand bed are 481mm long $\times$ 444mm wide $\times$ 200mm high. Along the sides are polycarbonate viewing windows.

In flight the model travels in the positive X direction. The earth gravity act in the negative Y direction and the radial accelerations due to the centrifugal accelerations act in the negative Z direction. The bumpy road impose shaking in $\pm$X direction and for horizontal accelerometers accelerations were defined as positive when acting in the positive X direction. In the case of vertical accelerometers positive accelerations were defined as positive when acting in the negative Z direction. For displacement measurements, vertical displacements were defined as positive in the positive Z direction and the horizontal displacements were defined as negative in the positive X direction. Looking from the front side of the model clockwise moments were defined as positive.

3.3. Model Construction

The models were prepared in a strong box (Fig 3.1) in which the instrumented pile foundation was embedded in dry sand (Plate 1). The models were instrumented with bending moment strain gauges glued to the piles, accelerometers and LVDT's in order to get measurements during swing up and, before, during and after earthquakes.

3.3.1. Foundation

Test AM-1

Test AM-1 was designed to study the earthquake behaviour of a single pile with a pile head. The pile was made of a thick walled aluminium alloy of external diameter 9.525 mm and internal diameter of 3.175 mm. The total length of the pile was 255 mm and the embedded length was 180mm. The pile cap was made of lead bounded at the top and bottom with brass plates. The pile cap was 40mm thick and had a cross-section of 50 $\times$ 50 mm weighing 1.07kg (Fig 3.2).

As stated in section 2.3.3. the pile was instrumented with eight full bridge circuits with the accelerometer attached to pile tip to measure the horizontal acceleration transmitted to the pile tip, in the direction of the shaking. Three accelerometers were attached to the pile head (Plate 4) to measure the accelerations transmitted to the pile head in the direction of shaking, in the direction perpendicular to the and in the vertical direction. The pile was aligned during pouring of sand, so that the strain gauges measure the induced bending moments in the direction of shaking.

Two LVDT's were attached to the pile head to measure the vertical static and dynamic settlement of the foundation as shown in the Fig 3.2 (Plate 4). One LVDT was attached horizontally to the pile head in the lateral direction of shaking. In case of the horizontal LVDT a small piece of copper wire was attached to its tip and subsequently glued to the pile head. Thus it was possible to measure the horizontal deflection even with a small amount of vertical settlement of the foundation.

Test AM-2

The test AM-2 was designed to study the earthquake response of piles with a small pile head (Fig 3.3). The same pile used in test AM-1 was used for this test but without the pile head. A small piece of angle was fixed to the pile to which two accelerometers were attached, one to measure the horizontal and the other to measure the vertical acceleration transmitted to the top of the pile. Two LVDT's were also attached to the pile to measure the horizontal and vertical, static and dynamic displacements (Plate 3).

Test AM-3

Test AM-3 was designed to study the earthquake response of a pile group (Fig 3.4). A group of four piles was used with two instrumented piles (Plate 6). Similar piles used in the previous tests were used in this test. The distribution of the strain gauges along the piles are shown in Fig 2.2. The piles were spaced at four times the pile diameter. The pile cap was 40mm thick and had a cross-section of 100 $\times$ 100 mm. This was made of steel, weighing 2.65 Kg. These four piles were rigidly clamped by the pile head.

All eight bending moment strain gauges on the first pile and only six out of eight on the second pile were connected to the junction box due to the limitation in the available channels.

As in test AM-1, an accelerometer was attached to both instrumented piles at the pile tip. The pile head was provided with an accelerometer to measure the horizontal acceleration transmitted to the pile head through the soil. Three LVDT's were also attached to measure the horizontal and vertical static and dynamic displacements as in test AM-1 (Plate 8).

3.3.2. Pouring of sand

All these tests were carried out in dry sand. The sand used in all these tests was dry Leighton Buzzard sand 52/100 (nominal grain size 0.225mm) was used for one of these test. The coding 52/100 refers to the British Standard sieves through which the sand should pass/be retained. The maximum and minimum voids ratio are 0.93 and 0.58 corresponding to the relative densities of 0% and 100% respectively (Mak, 1984).

The hopper height from the strong box and the rate of flow were adjusted to get dense packed sand model. It was found that by pouring very slowly from a height of 0.6 m samples could be made with relative density close to the 100%. Sand was glued to the base of the strong box to ensure a rough surface. In the case of the test with the pile group (AM-3) the strong box was slightly vibrated during sand pouring to ensure a uniform dense soil layer in between the piles (Plate 7).

Pouring of sand was intermitted in order to place the accelerometers (Plate 2). Care was taken to align the accelerometers to measure the accelerations in the direction of shaking. Some accelerometers were placed to measure the vertical accelerations in the soil. A measuring rack was used to position the accelerometers accurately (Plate 1). After pouring the first 20mm of sand layer the model pile was placed vertically at the centre of the strong box with the use of the clamp from the gantry (Plate 2). The sand pouring and the placement of accelerometers were continued till the required depth of 200mm depth of sand layer was achieved. An accelerometer was also attached to the strong box to measure the input acceleration. The duxseal of thickness 70mm and height of 180mm was placed on the both sides of the model before pouring the sand, in order to reduce the boundary effects.

The probes of vertical LVDT's were rested on the pile cap while the horizontal LVDT probe was glued to the pile cap. The body of the LVDT was attached to the gantry by a bracket. The deflection of the LVDT gantries during flight were considered when analysing the LVDT time history records.

Calibration of all the instruments and testing of the electrical systems were carried out on the lab floor before the package was hung on the centrifuge arm. The position of the accelerometers were also measured using the measuring rack after the test by careful excavation. The position of the various accelerometers and the LVDTs were tabulated in Table 2-4.

3.4. Centrifuge test

3.4.1. Swing up

The completed model was mounted on the centrifuge arm. The transducer readings were noted at 1'g' before swing up. The centrifuge was accelerated to 80g gradually. The bending moment along the pile and the displacement of the pile cap were observed at various 'g' levels during swing up (at 10g,20g,40g,60g and at 80g). The offsets were adjusted where necessary.

3.4.2. Firing of Earthquakes

A series of earthquakes were fired for each test at 80g and the time records of the transducers were captured by two high speed Racal Analogue tapes. The plots of the short-term time records of the various transducers are shown in Figs 3.5-3.16. The permanent displacements of the foundation and the residual bending moments along the pile after each earthquake was also observed.

3.4.3. Swing Down

After firing a series of earthquakes the acceleration of the centrifuge was reduced and was stopped. Again a set of transducer readings were noted at 1'g'.

The position of the accelerometers were checked using a measuring rack, after the test by careful excavation.

4. Presentation of Data

The distribution of the strain gauges along the piles are shown in fig 2.2. The transducer locations in the model are shown in fig 3.2-3.4 and are reported in tables 2-4. The bending moments observed along the piles during swing up and after earthquakes are shown in tables 6,8 and 10a,b, for tests AM-1,AM-2 and test AM-3 respectively. The corresponding displacements observed in the pile foundation are tabulated in table 5,7 and 9 for test AM-1,AM-2 and test AM-3 respectively.

The short term records during earthquakes are presented in next, two sheets for each event (Figs. 3.5-3.16). These are raw data (not subjected to any filtering or smoothing) and contains 1024 digitised points. The pile foundation data, soil data and the centrifuge data are summarised in the Appendix. At the bottom left of the plot are shown the test and model identifiers, flight number, event type and number. On the right the value of 'g' level at the model centroid and the mean peak (K_m) and the absolute peak (K_p) earthquake strengths (expressed as a percentage of the gravities at the model centroid radius) are shown for the model. The plot has the scale of the model and this information is presented above the title box. The time records are all plotted on the same time axis, the units being marked below the first record and above the test record. On the right of the time record the transducer type and number are given. The abbreviations used for the bending moment transducer, the Linear variable differential transformer and the accelerometer are BMT, LVDT and ACC respectively. The scales are printed in the axis in the engineering units. The figure given is that represented by 1cm, which is the distance between the thick marks straddling the vertical axis. On the left of the time record, double cross-marks shows the maximum and minimum levels of the plotted samples. These are based on a zero level which is fixed by the mean of the first 4% of the reduced samples.

The annotation 'PAP' appearing on some of the records indicates 'Possible Accuracy Problems'. The annotations 'OTRR' and 'OTLL' stands for 'Outside Recordable Range' and 'Outside Linear Range' respectively.

A set of photographs are also presented to show the various stages of the model preparation (Plate 1-8).

References

1. Schofield, A. N. 'Dynamic and Earthquake Geotechnical Centrifuge Modelling', 1981, Proc. Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, Vol. 3, Missouri, U. S. A.,pp 1081-1100.
2. Schofield, A. N. 'Cambridge Geotechnical Centrifuge Operations', 1980, Geotechnique 30, 3, pp 227-268.
3. Kutter, B. L. 'Centrifugal Modelling of the Response of Clay Embankments to Earthquakes', 1983, Ph. D. Thesis, Cambridge University.
4. Edgcombe, K. 'Fly 14 User Manual', (unpublished), 1986, Cambridge University Engineering Department.

APPENDIX

Pile Data (Test AM-1, AM-2, AM-3)

Length of the pile = 255 mm
External diameter = 9.525 mm
Internal diameter = 3.175 mm
Mass density of the pile shaft = 0.173 kg/m
Modulus of elasticity of the pile material = 7.58 $\times 10^4$ N/mm^2
Moment of inertia of the pile shaft = 399.1 mm^4

Pile Cap Data

Test AM-1

Cross-section of the pile cap = $50mm \times 50mm$
Height of the pile cap = 40 mm
Weight of the pile cap = 1.08 kg

Test AM-3

Cross-section of the pile cap = $100mm \times 100mm$
Height of the pile cap = 40mm
Weight of the pile cap = 2.65 kg

Centrifuge Test Data

Centrifugal acceleration at the mid sand layer = 80g

Soil Properties (Mak, 1984)

Type: Leighton Buzzard 52/100 sand.

D_{95}(mm)=0.30

D_5(mm) =0.15

e_{max}=0.928

e_{min}=0.585

ϕ_c(critical state)=33°

ϕ_{max}=51°

Voids ratio in the model sand bed=0.6

(Relative density=91%)

G(specific gravity)=2.65

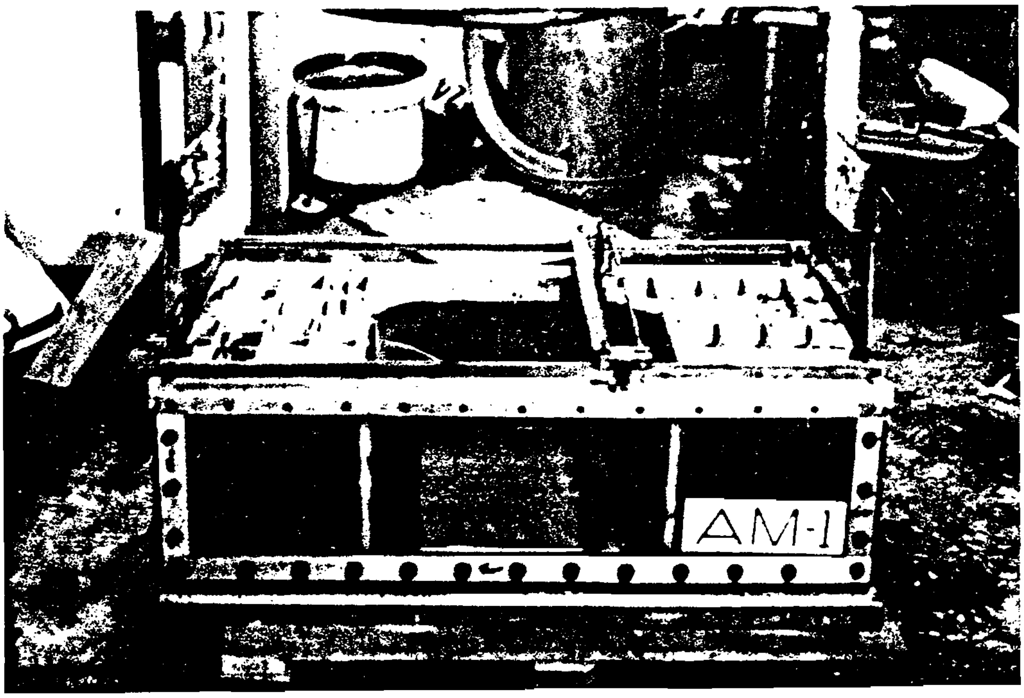


Plate 1. A view of the strong box with the measuring rack attached.

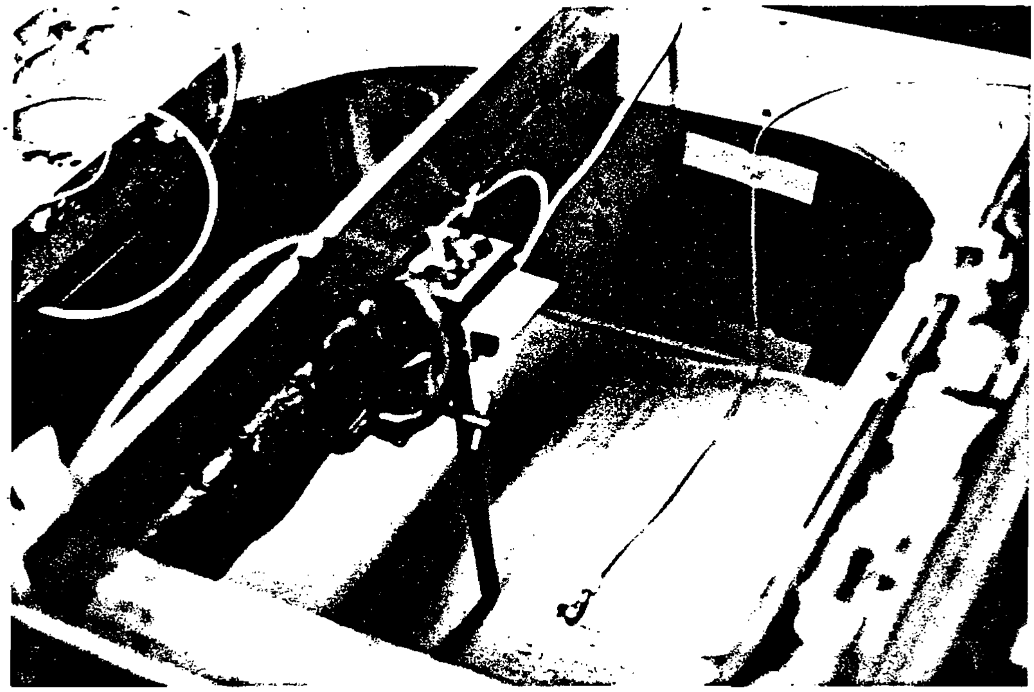


Plate 2. Placement of accelerometers during construction of the model AM-1. Model Pile clamped to a gantry.

Plate 3. Close-up of the pile head (Model AM-2) showing the attachment of accelerometers and LVDTs.

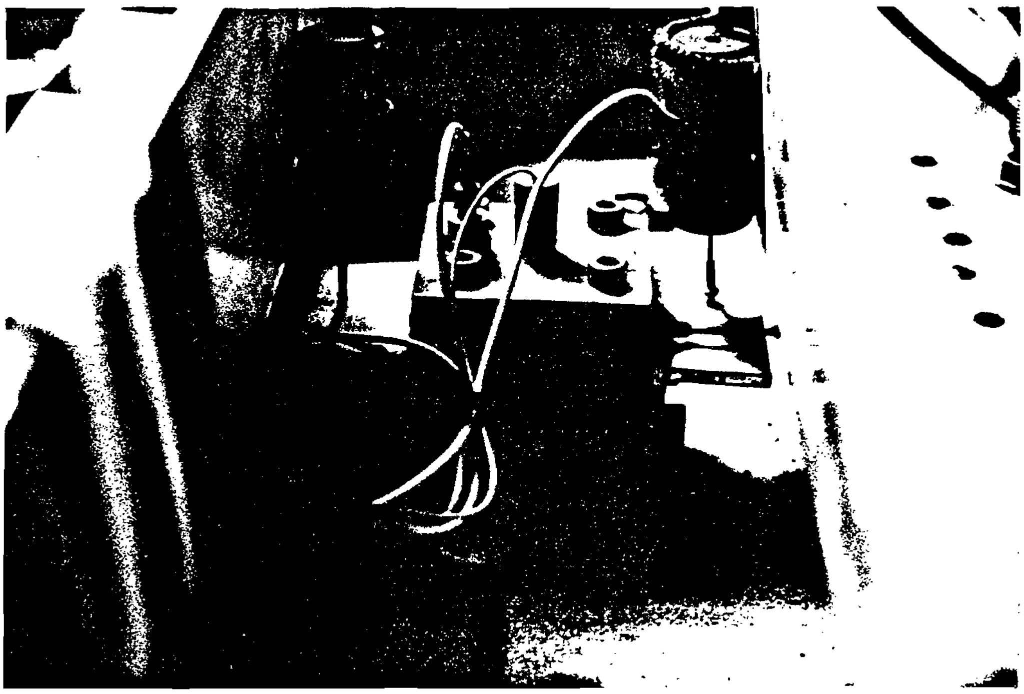


Plate 4. Close-up of the pile top (Model AM-1) showing the attachment of accelerometers and LVDTs.

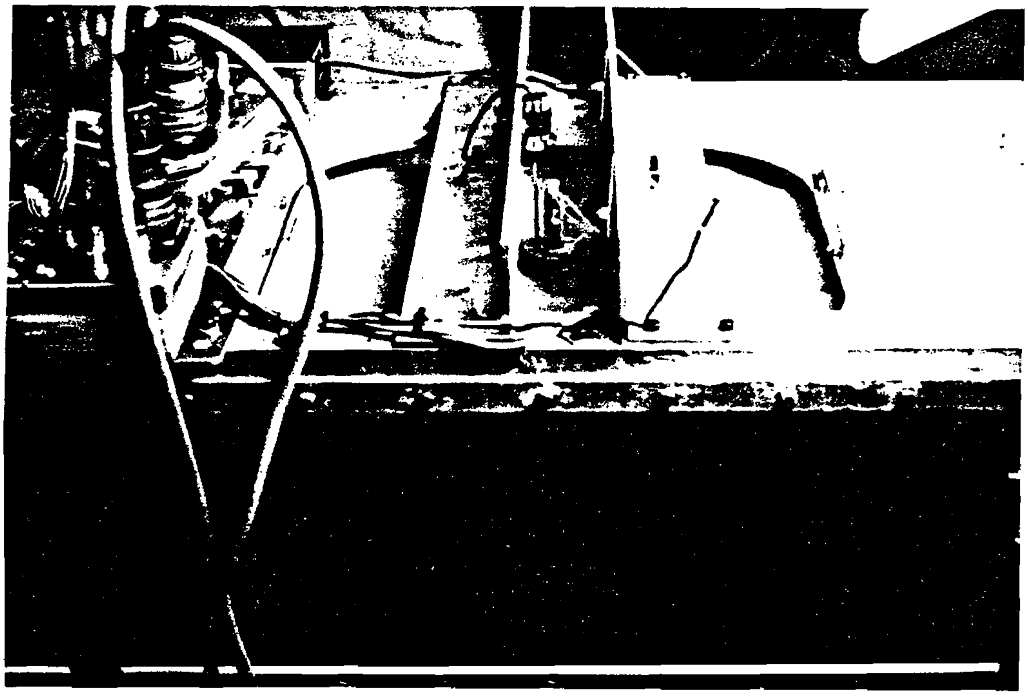


Plate 5. Completed model with junction boxes.

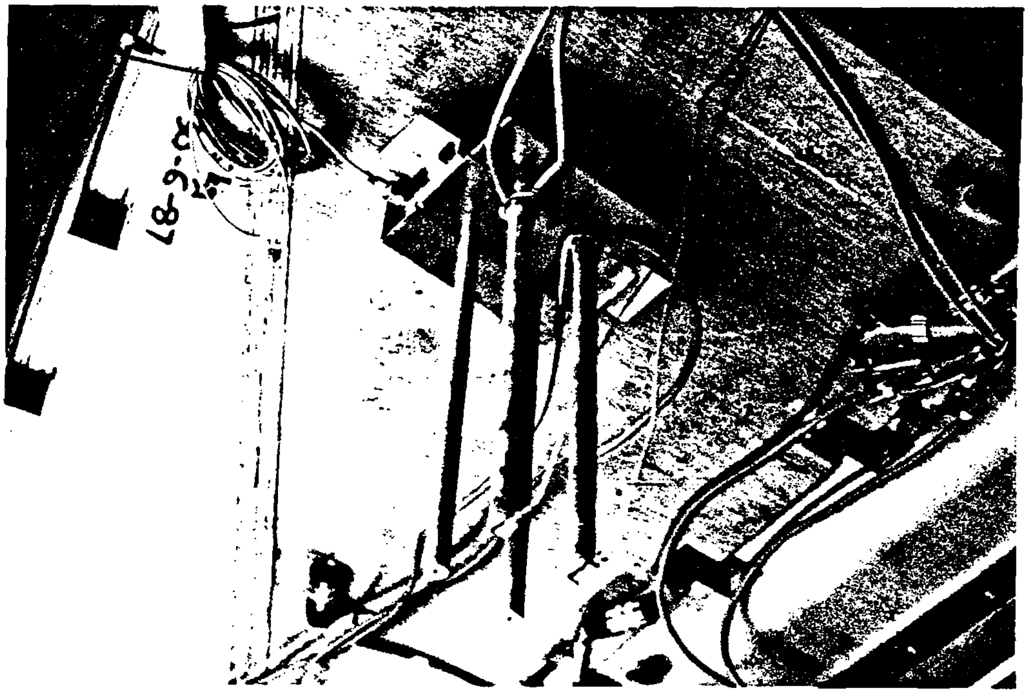


Plate 6. Close-up of the pile group (Model AM-3) showing the instrumented piles and attachment of accelerometers.

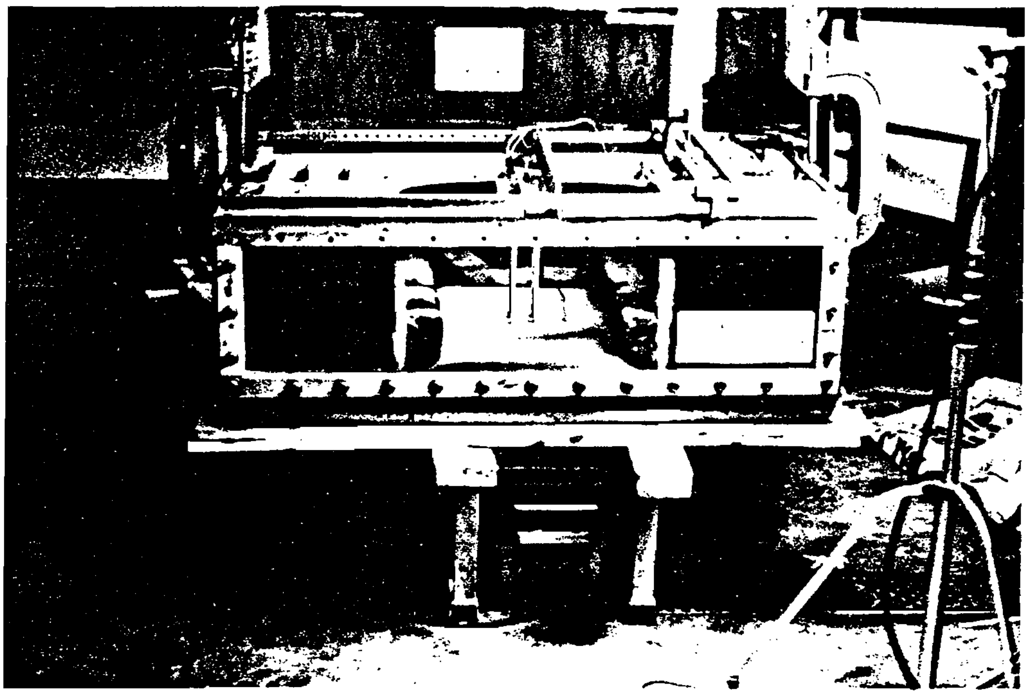


Plate 7. Construction of model AM-3 showing the attachment of vibrater to the strong box.

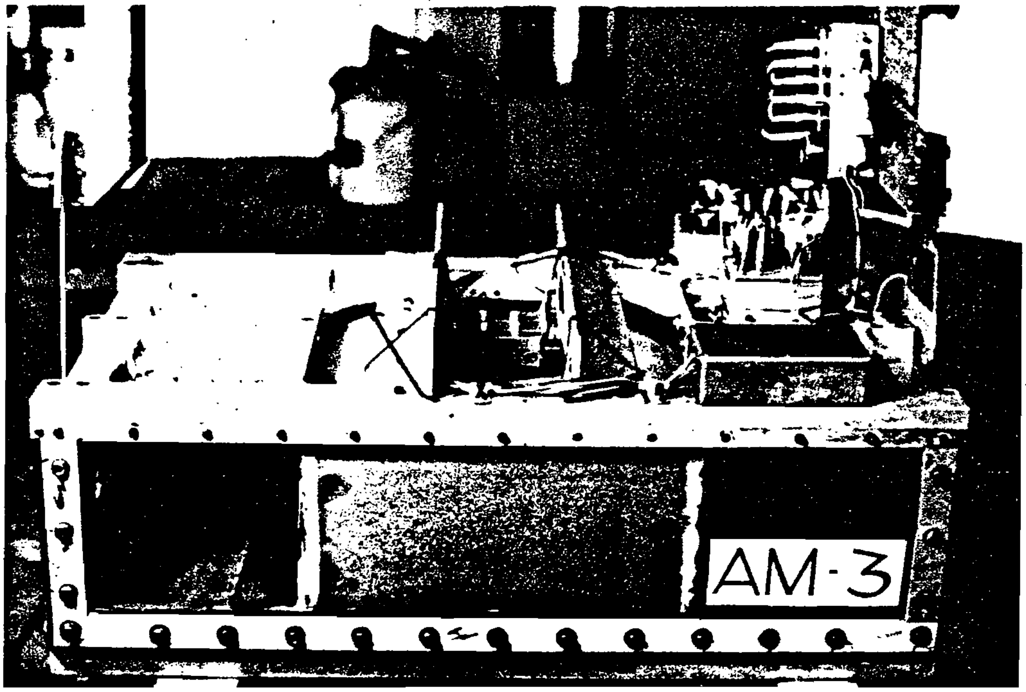


Plate 8. Completed model with junction boxes.

Table 1

Summary of scaling ratios

Quantity	*Ratio of Model to Prototype*
Length	$\frac{1}{N}$
Area	$\frac{1}{N^2}$
Volume	$\frac{1}{N^3}$
Mass	$\frac{1}{N^3}$
Mass density	1
Weight density	$\frac{1}{N}$
Force	$\frac{1}{N^2}$
Velocity	1
Acceleration	N
Stress	1
Strain	1
Energy	$\frac{1}{N^3}$
Frequency	N
Time (dynamic)	$\frac{1}{N}$
Bending Moment	$\frac{1}{N^3}$
Bending Stiffness	$\frac{1}{N^4}$

Table 2

Location of transducers for Test AM-1

Transducer	*General Location*	$X(mm)$	$Y(mm)$	$Z(mm)$
ACC 1258	Attached to the box	–	–	–
ACC 3486	Attached to the box	–	–	–
ACC 1900	Bottom Sand Layer	50	00	20
ACC 1544	Top Sand Layer	50	00	180
ACC 1925	Top Sand Layer	-125	00	180
ACC 1552	Pile Cap (direction of shaking)	-25	-25	260
ACC 27	Pile Tip	00	00	20
ACC 1938	Bottom sand Layer (vertical)	-50	00	45
ACC 1572	Pile Cap (direction perpendicular to shaking)	00	25	240
ACC 3478	Pile Cap (vertical)	20	00	260
ACC 1932	Bottom Sand Layer	100	00	60
ACC 3492	Middle Sand Layer	50	00	120
ACC 1486	Middle Sand Layer	-70	00	140
ACC 3479	Top Sand Layer	50	00	160
LVDT 7448	Pile Head (vertical)	40	00	245
LVDT 7451	Pile Head (vertical)	-40	00	245
LVDT 7445	Pile Head (lateral)	-25	00	250

Co-ordinate system shown in fig. 3.1

Table 3

Location of transducers for test AM-2

Transducer	*General Location*	$X(mm)$	$Y(mm)$	$Z(mm)$
ACC 1258	Attached to the box	–	–	–
ACC 3486	Attached to the box	–	–	–
ACC 1900	Bottom Sand Layer	50	00	20
ACC 1932	Bottom Sand Layer	100	00	60
ACC 1552	Pile Cap (direction of shaking)	00	00	230
ACC 27	Pile Tip	00	00	20
ACC 1938	Bottom sand Layer (vertical)	-50	00	20
ACC 3492	Middle Sand Layer	50	00	80
ACC 1486	Middle Sand Layer	50	00	140
ACC 1544	Top Sand Layer (vertical)	-50	00	160
ACC 3479	Top Sand Layer	50	00	160
ACC 3478	Top Sand Layer	-50	00	180
ACC 1572	Top Sand Layer	50	00	180
ACC 1925	Pile (vertical)	-15	10	205
LVDT 7448	Pile Top (vertical)	12.5	00	220
LVDT 7451	Pile Top (lateral)	00	00	230

Co-ordinate system shown in fig 3.1

Table 4
Location of transducers for Test AM-3

Transducer	*GeneralLocation*	$X(mm)$	$Y(mm)$	$Z(mm)$
ACC 3479	Attached to the box	–	–	–
ACC 1544	Bottom sand layer	80	00	20
ACC 3457	Middle sand layer	-80	00	120
ACC 728	Top sand layer	80	00	180
ACC 1552	Pile cap(direction of shaking)	50	-35	243
ACC 74	Pile tip 1	-20	00	20
ACC 76	Pile tip 2	20	00	20
LVDT 7445	Pile Cap(vertical	-67.5	00	248
LVDT 7451	Pile cap(vertical)	67.5	–	248
LVDT 1	Pile Cap(lateral)	-50	00	250

Co-ordinate system shown in fig 3.1

Table 5
Displacement of the pile cap during swing up and after earthquakes (Test AM-1)

Stage of the test	Displacement /(mm.)		
	LVDT 7448 (vertical)	LVDT 7451 (vertical)	LVDT 7445 (Horizontal)
At 10g	-0.023	-0.196	0.178
At 20g	-0.035	-0.316	0.356
At 40g	0.021	-0.480	0.655
At 60g	0.030	-0.691	0.891
At 80g	-0.016	-0.919	1.095
After EQ1	-0.035	-1.175	1.455
After EQ2	-0.069	-1.180	1.491
After EQ3	-0.108	-1.264	1.584
After EQ4	-0.131	-1.324	1.635
After Swing down	-0.600	-0.811	0.465

Co-ordinate system shown in fig 3.1

Table 6

Bending moments along the pile during swing up and after earthquakes (Test AM-1)

Stage of the test	Bending Moments /(N.mm.)							
	BMT1	BMT2	BMT3	BMT4	BMT5	BMT6	BMT7	BMT8
At 10g	-26.5	-63.4	-150.8	-202.5	-266.5	-226.1	-222.4	-188.9
At 20g	-33.2	-90.3	-278.0	-451.5	-570.7	-524.9	-503.9	-403.2
At 40g	-26.8	-96.2	-466.5	-924.7	-1236.3	-1202.2	-1168.6	-932.6
At 60g	-32.1	-55.9	-553.4	-1287.3	-1842.9	-1845.9	-1821.7	-1466.7
At 80g	-62.6	-15.5	-613.4	-1605.3	-2430.5	-2479.9	-2478.0	-2016.2
After EQ1	-100.2	-222.4	-1198.7	-2609.3	-3247.8	-3025.0	-2791.0	-2120.5
After EQ2	-96.0	-229.6	-1239.5	-2706.4	-3361.6	-3093.8	-2858.2	-2180.2
After EQ3	-120.5	-325.5	-1422.2	-2919.8	-3479.5	-3168.3	-2903.8	-2205.2
After EQ4	-114.1	-348.7	-1515.4	-3063.1	-3549.5	-3197.1	-2934.9	-2227.1
After Swing down	-53.6	-260.9	-333.7	-277.4	-169.5	-53.5	-77.7	-81.1

Co-ordinate system shown in fig. 3.1

Sign conventions given in section 3.2

Table 7

Displacement of the pile during swing up and after earthquakes (Test AM-2)

Stage of the test	Displacement (mm.)	
	LVDT 7448 (vertical)	LVDT 7451 (Horizontal)
At 10g	-0.005	-0.082
At 20g	-0.011	-0.036
At 40g	0.099	0.055
At 60g	0.152	0.113
At 80g	0.186	0.173
After EQ1	0.207	0.240
After EQ2	0.173	0.247
After EQ3	0.170	0.268
After EQ4	0.157	0.273
After EQ5	0.147	0.273
After Swing down	0.018	-0.022

Co-ordinate system shown in fig 3.1

Table 8

Bending moments along the pile during swing up (Test AM-2) and after earthquakes

Stage of the test	Bending Moments (N.mm.)							
	BMT1	BMT2	BMT3	BMT4	BMT5	BMT6	BMT7	BMT8
At 10g	-5.7	7.0	2.0	-8.5	-40.6	-7.4	-32.1	-24.0
At 20g	1.7	0.1	-30.9	-59.7	-95.8	-63.9	-82.6	-68.0
At 40g	9.8	4.7	-81.3	-165.7	-230.2	-200.0	-212.5	-188.9
At 60g	17.8	14.6	-110.6	-246.5	-346.4	-318.3	-333.8	-299.8
At 80g	22.2	27.5	-145.6	-345.8	-495.3	-462.7	-478.1	-433.0
After EQ1	28.9	-55.2	-362.0	-560.8	-569.4	-496.3	-507.0	-456.0
After EQ2	28.1	-56.7	-380.2	-580.1	-602.8	-495.6	-527.2	-491.3
After EQ3	20.0	-80.2	-407.3	-604.5	-621.7	-494.9	-544.5	-507.9
After EQ4	18.3	-81.8	-408.7	-616.1	-642.1	-496.3	-555.3	-523.0
After EQ5	16.7	-82.5	-408.7	-613.3	-644.2	-494.1	-562.6	-528.0
After Swing down	-16.4	-43.8	-44.8	-68.9	-67.5	-67.6	-37.2	-76.6

Co-ordinate system shown in fig 3.1 and sign conventions given in section 3.2

Table 9

Displacement of the pile group during swing up and after earthquakes (Test AM-3)

Stage of the test	Displacement /(mm.)		
	LVDT 7451 (vertical)	LVDT 7452 (vertical)	LVDT 1 (Horizontal)
At 10g	-0.040	-0.119	0.059
At 20g	-0.067	-0.219	0.102
At 40g	-0.043	-0.319	0.200
At 60g	-0.043	-0.382	0.259
At 80g	-0.052	-0.456	0.317
After EQ1	-0.139	-0.666	0.406
After EQ2	-0.236	-0.892	0.479
After EQ3	-0.317	-1.050	0.533
After Swing down	-0.300	-0.500	0.170

Co-ordinate system shown in fig 3.1

Table 10a

Bending moments along the pile during swing up and after earthquakes (Test AM-3)

Stage of the test	Bending Moments (N.mm.)							
	BMT11	BMT12	BMT13	BMT14	BMT15	BMT16	BMT17	BMT18
At 10g	-145.0	137.0	120.0	-136.0	99.0	65.0	52.0	0.0
At 20g	-277.0	269.0	245.0	-268.0	186.0	124.0	91.0	0.0
At 40g	-542.0	540.0	502.0	-510.0	326.0	210.0	151.0	-7.0
At 60g	-709.0	1903.0	661.0	-662.0	413.0	255.0	184.0	-17.0
At 80g	-860.0	3689.0	828.0	-828.0	494.0	292.0	115.0	-18.0
After EQ1	-803.0	884.0	921.0	-1144.0	873.0	568.0	341.0	-30.0
After EQ2	-899.0	995.0	1047.0	-1324.0	1076.0	739.0	436.0	-45.0
After EQ3	-953.0	1062.0	1124.0	-1436.0	1215.0	858.0	480.0	-46.0
After Swing down	92.0	1190.0	48.0	-110.0	159.0	217.0	176.0	2.0

Co-ordinate system shown in fig 3.1

Sign conventions given in section 3.2

Table 10b

Bending moments along the pile during swing up (Test AM-3) and after earthquakes

Stage of the test	Bending Moments / (N.mm.)					
	BMT21	BMT22	BMT23	BMT24	BMT25	BMT26
At 10g	-166.6	-163.0	-142.3	-123.4	-76.6	-63.9
At 20g	-326.9	-319.9	-266.7	-231.9	-130.9	179.3
At 40g	-647.5	-585.8	-467.1	-387.8	-198.7	179.3
At 60g	-850.0	-763.2	-591.5	-476.0	-225.8	-668.6
At 80g	-1038.0	-906.4	-688.2	-557.3	-246.1	-620.0
After EQ1	-1100.6	-1063.2	-901.8	-850.2	-553.9	-70.9
After EQ2	-1247.0	-1220.1	-1019.9	-970.2	-663.8	-503.9
After EQ3	-1345.2	-1308.1	-1086.3	-1029.9	-707.2	-612.3
After Swing down	-3.5	-30.7	-18.0	-53.6	-86.8	242.6

Co-ordinate system shown in fig 3.1

Sign conventions given in section 3.2

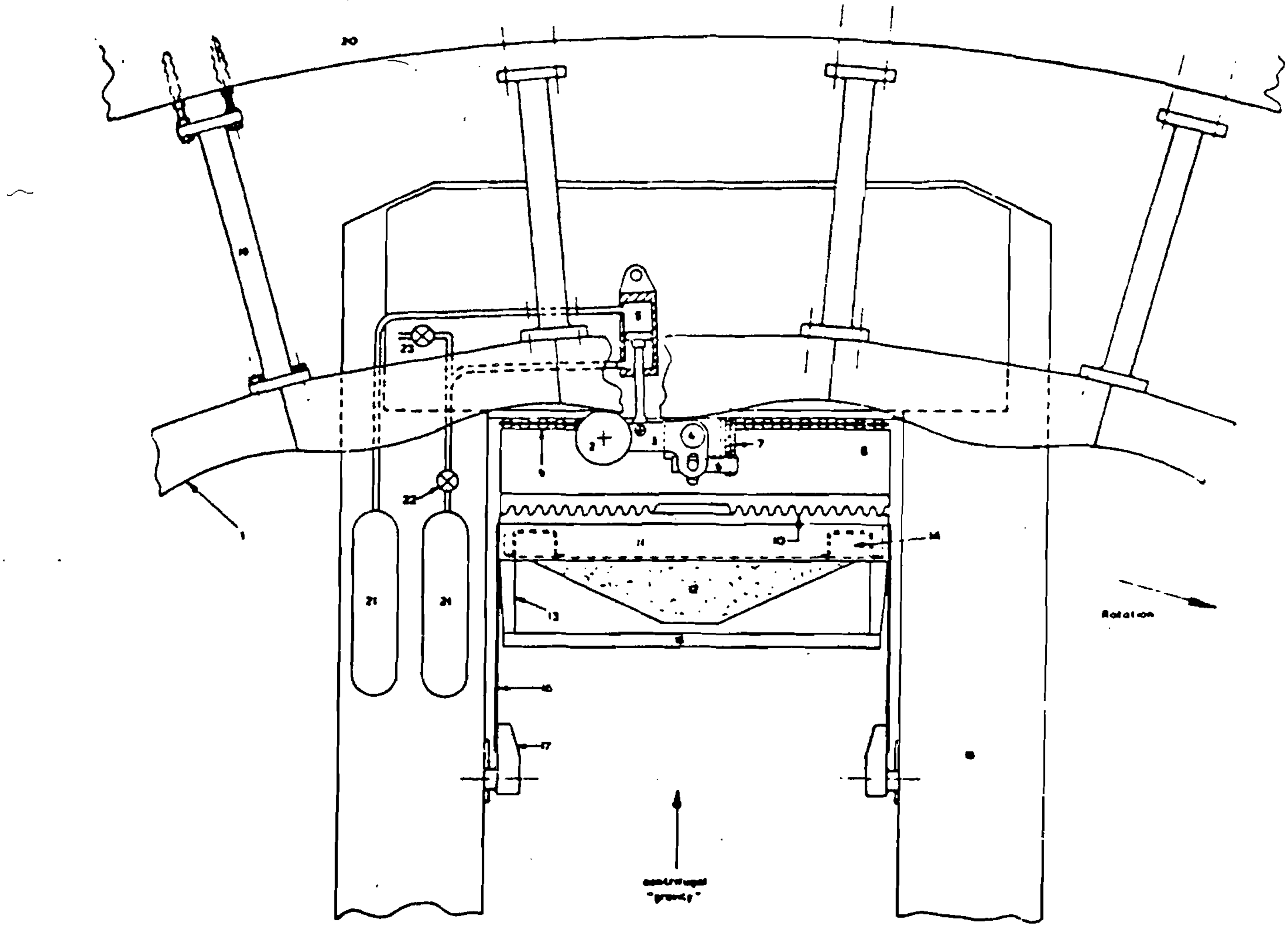


Fig. 2.1(a) Schematic view of Bumpy Road Apparatus looking downward into centrifuge pit. The specimen container is shown in its swung up and seated position.

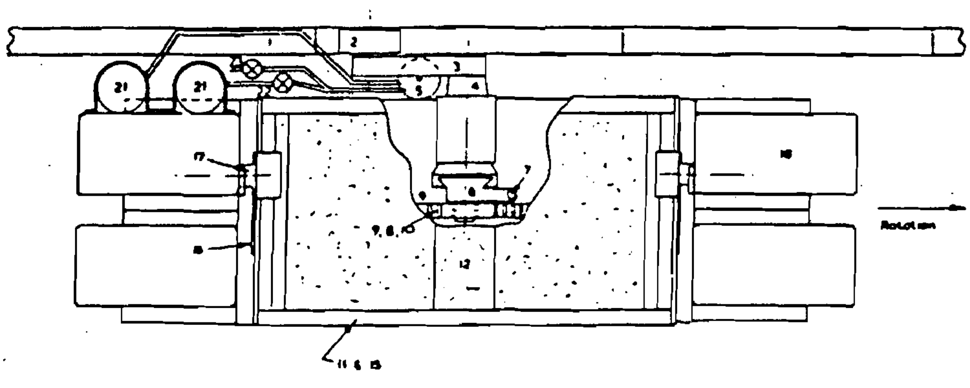


Fig. 2.1(b) Schematic view of Bumpy Road Apparatus looking radially outward from centrifuge axis. There is a cutaway view through the swinging specimen container.

ALL DIMENSIONS IN mm.

Fig. 2.2(a) Location of strain gauges along the pile (Test AM-1, AM-2).

(b) Location of strain gauges along the pile (Test AM-3).

(c) Arrangement of full bridge circuit.

(d) Section of the pile showing the location of the strain gauges.

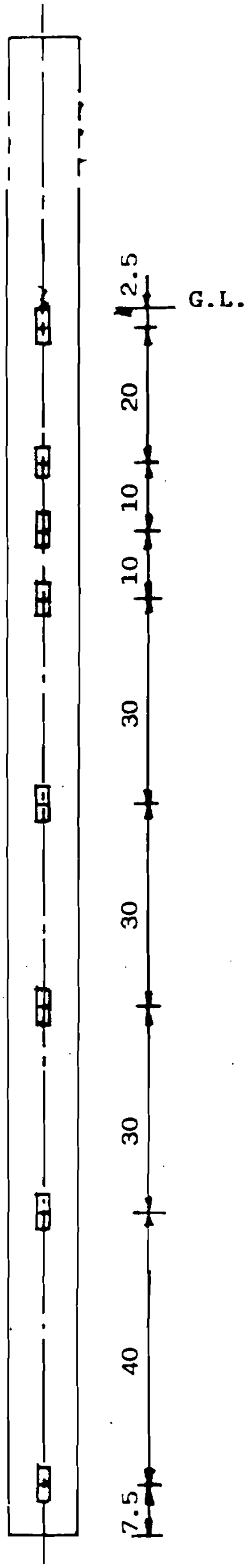


Fig. 2.2(a)

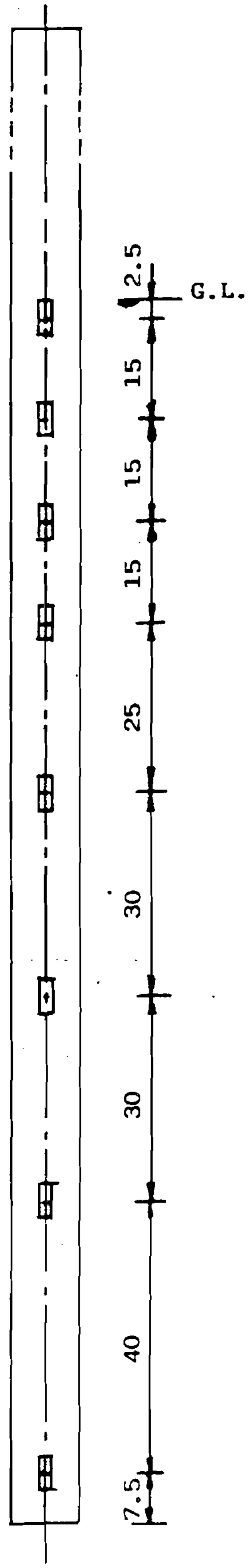


Fig. 2.2(b)

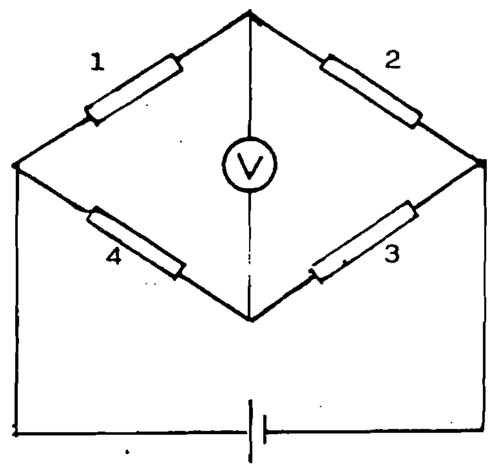
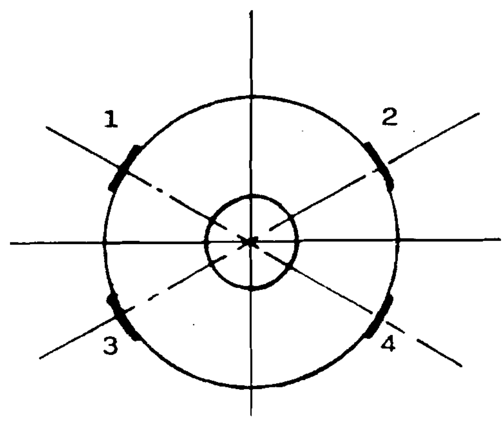


Fig. 2.2(c)



DIRECTION OF SHAKING

Fig. 2.2(d)

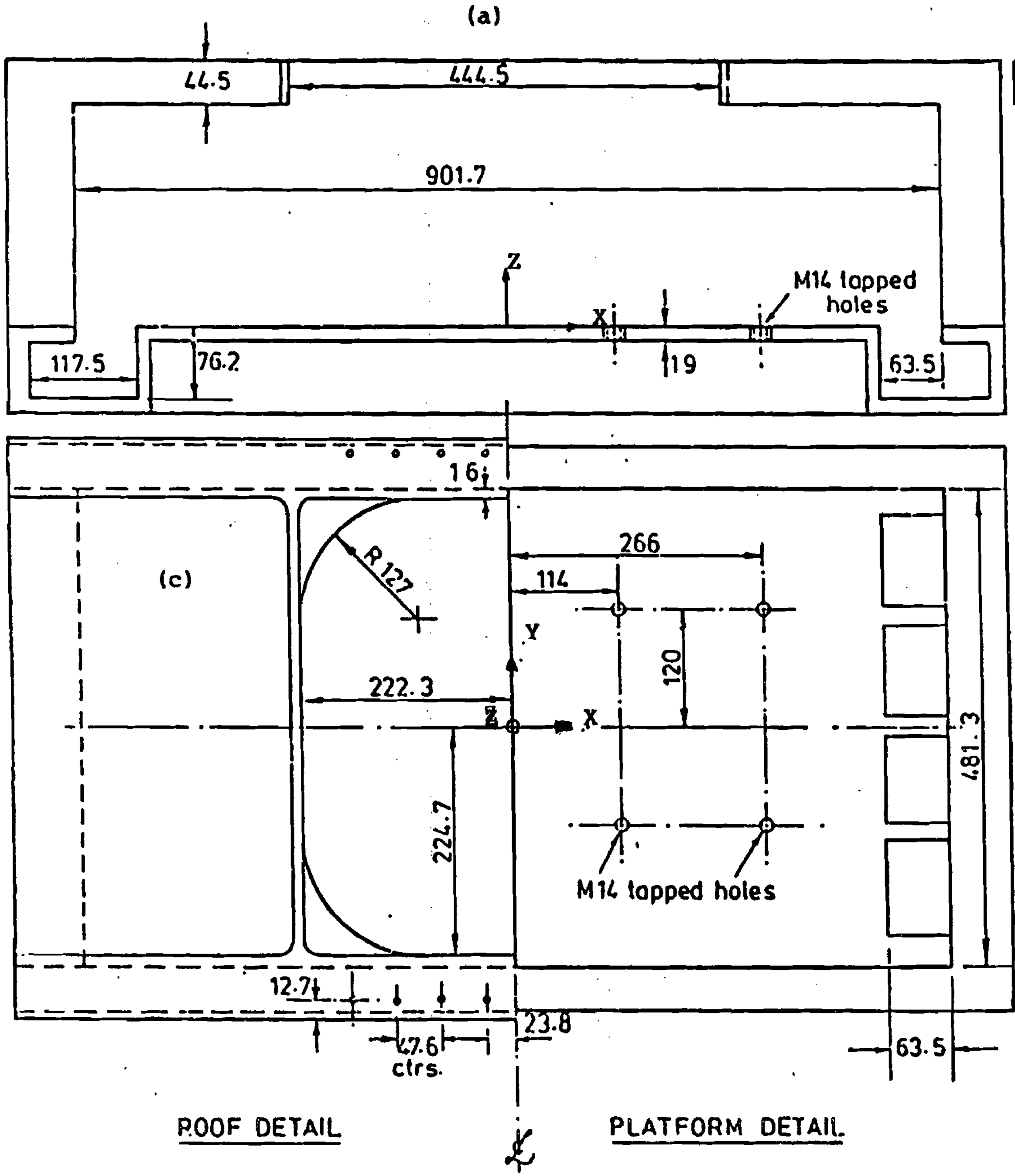


Fig. 3.1 Dimensions of swinging container.

(a) side view
(b) end view
(c) plan view

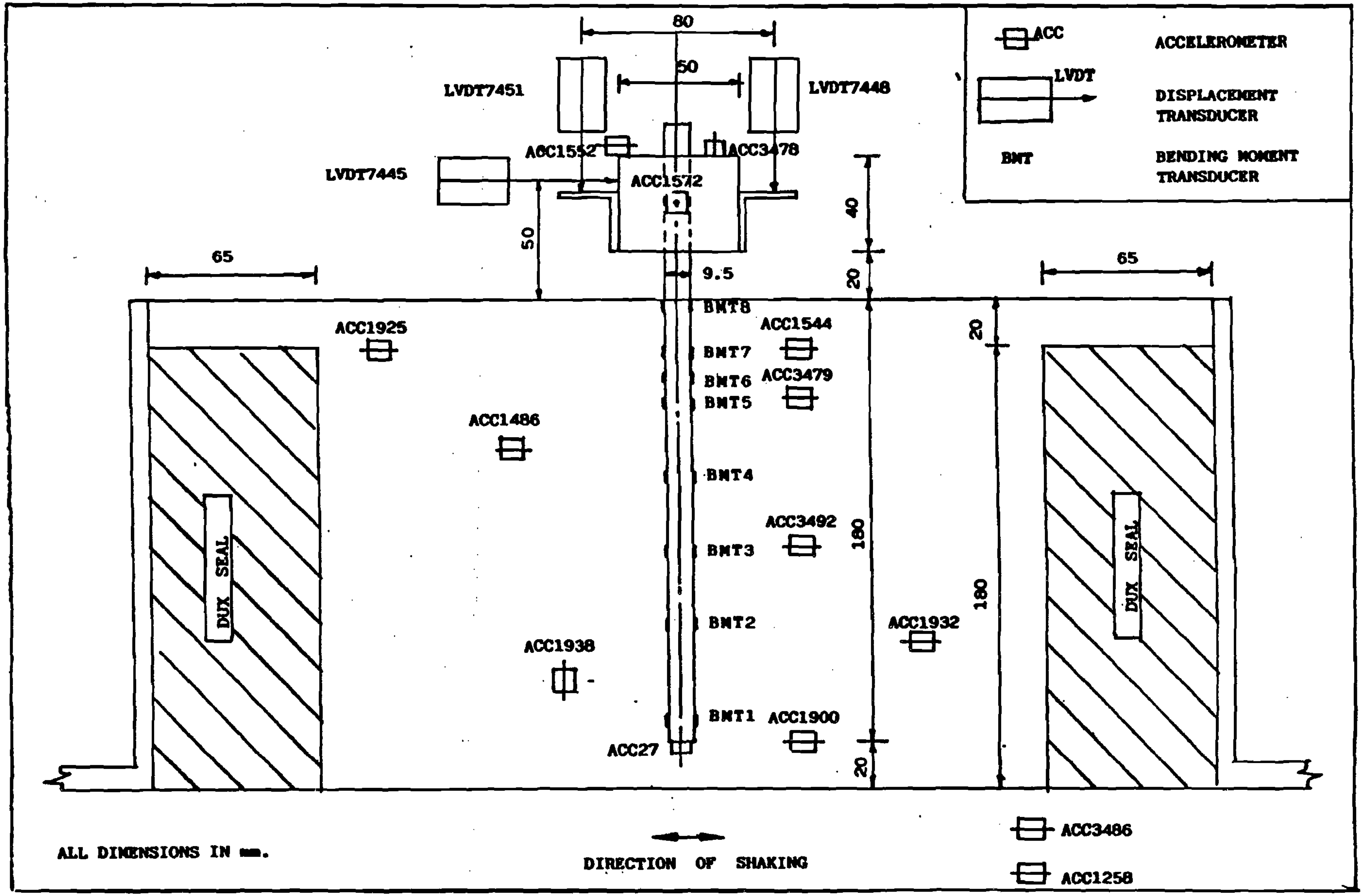


Fig 3.2 Dimensions And Instrumentation For Model AM-1

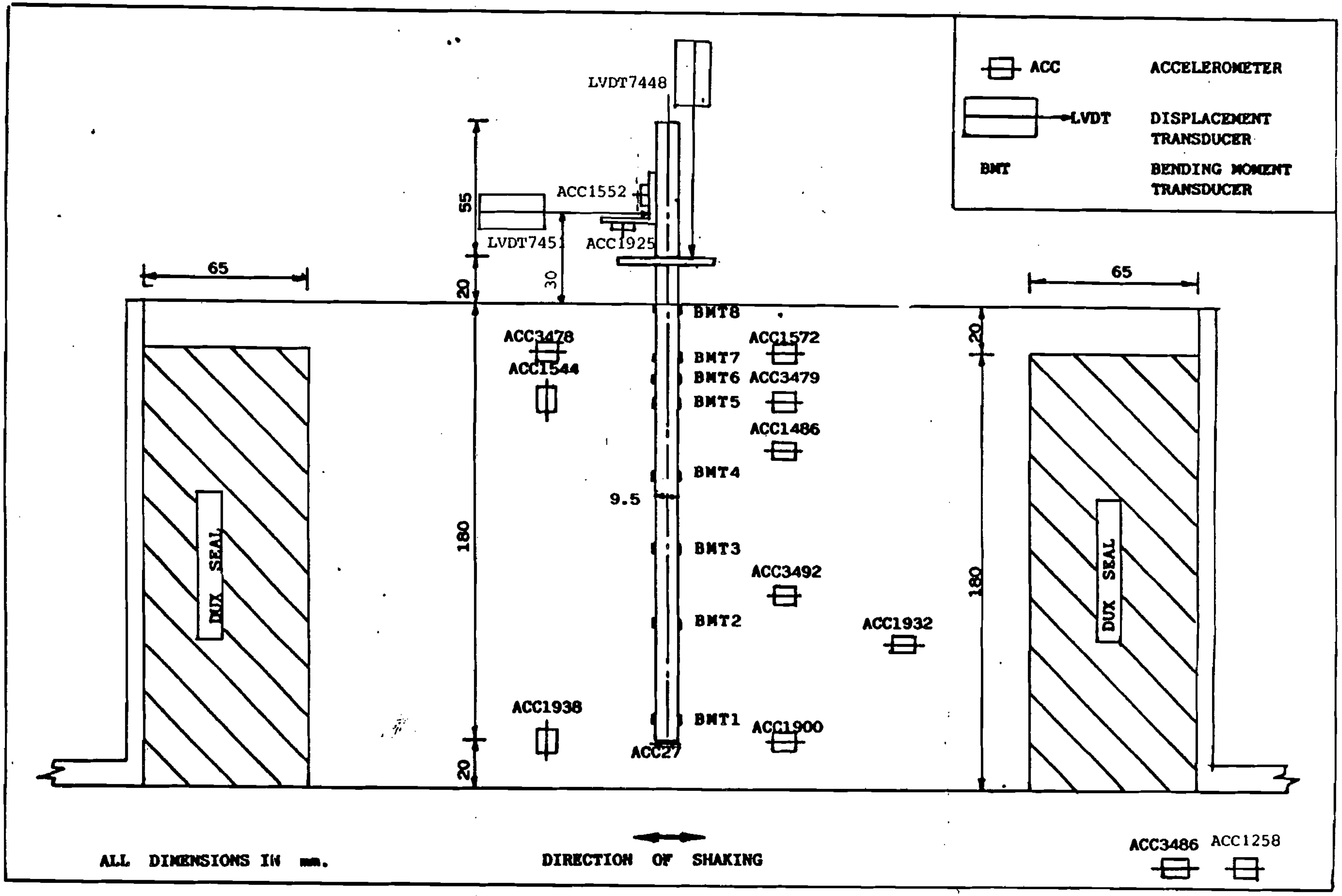


Fig 3.3 Dimensions And Instrumentation For Model AM-2

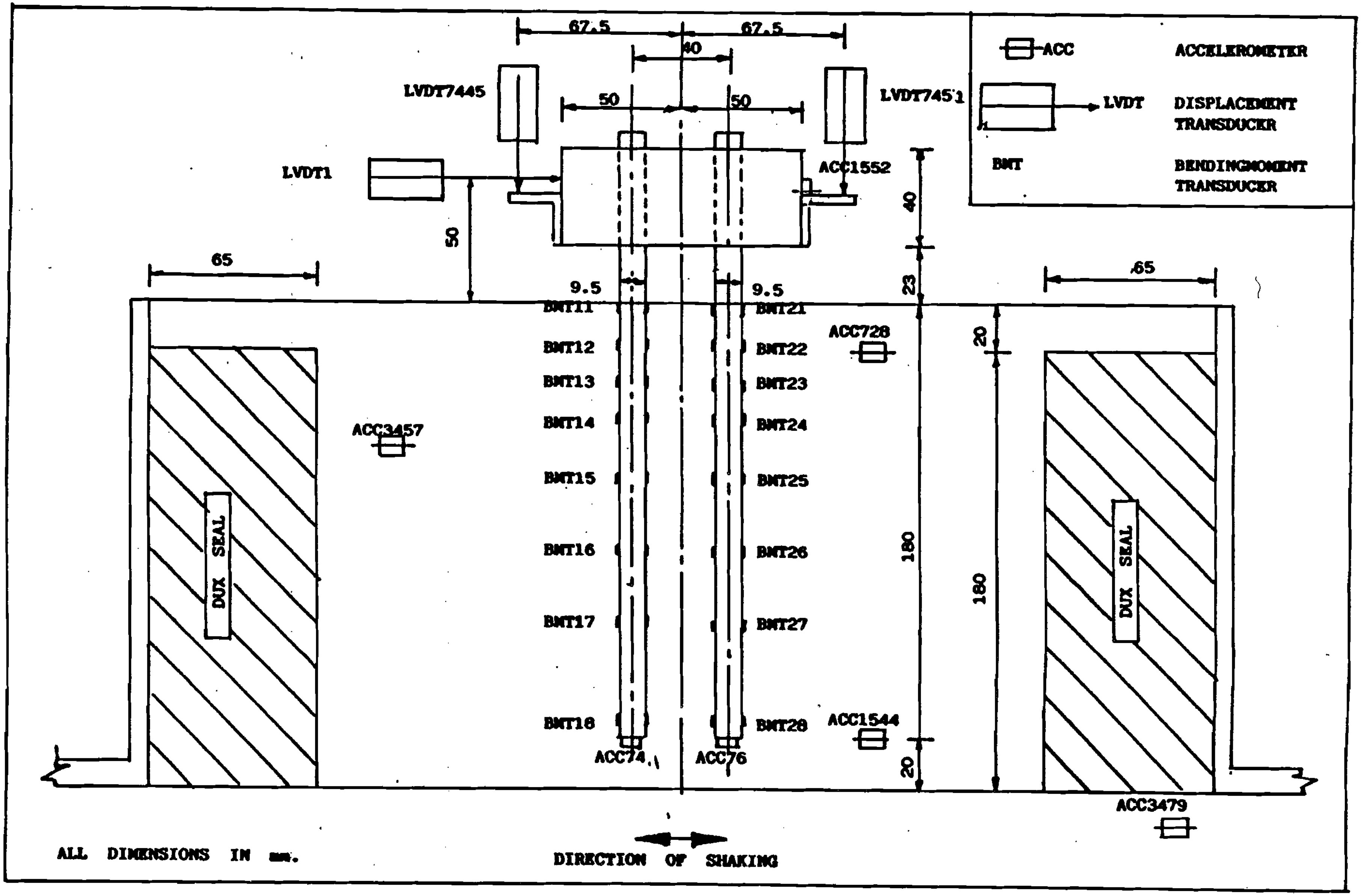
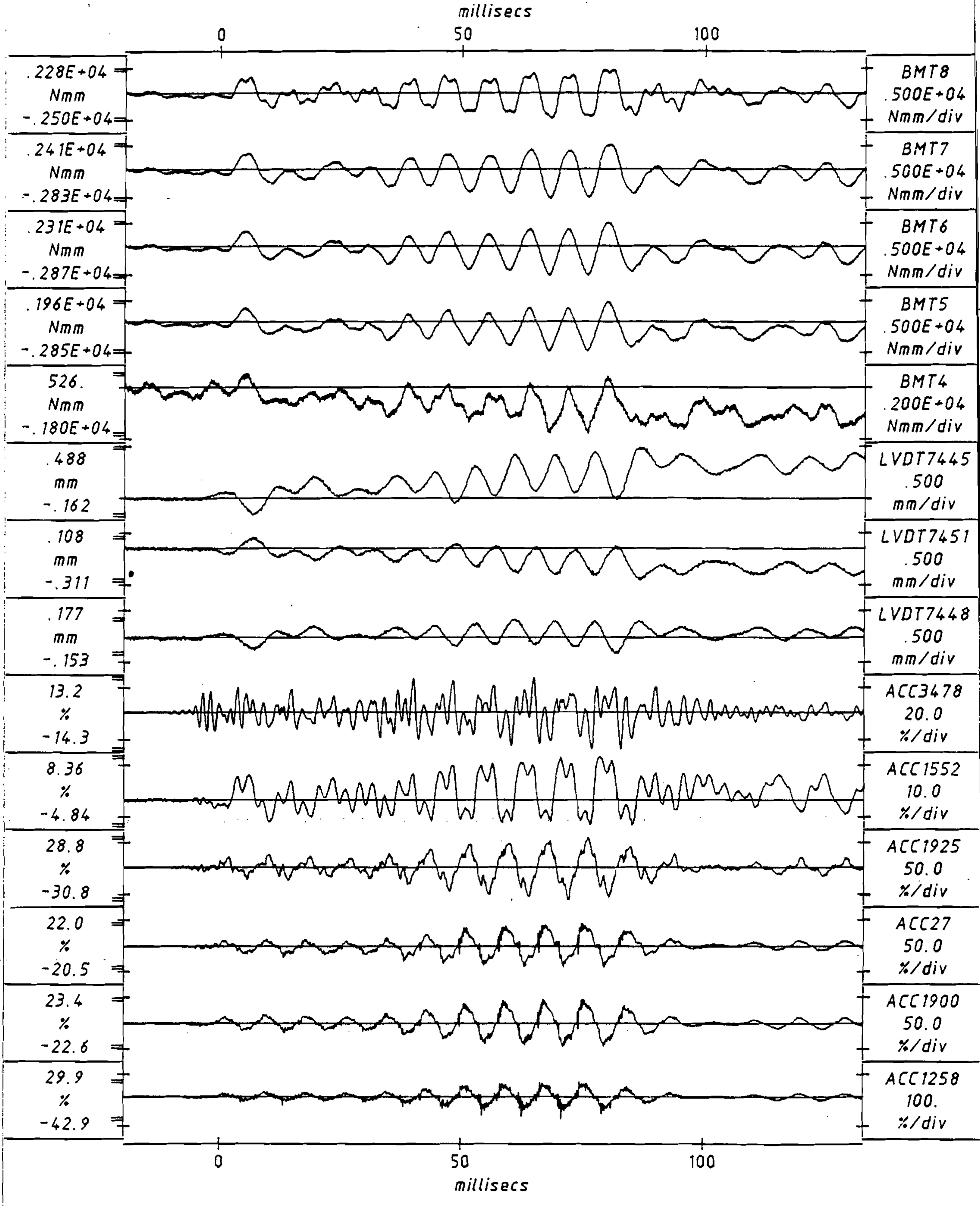


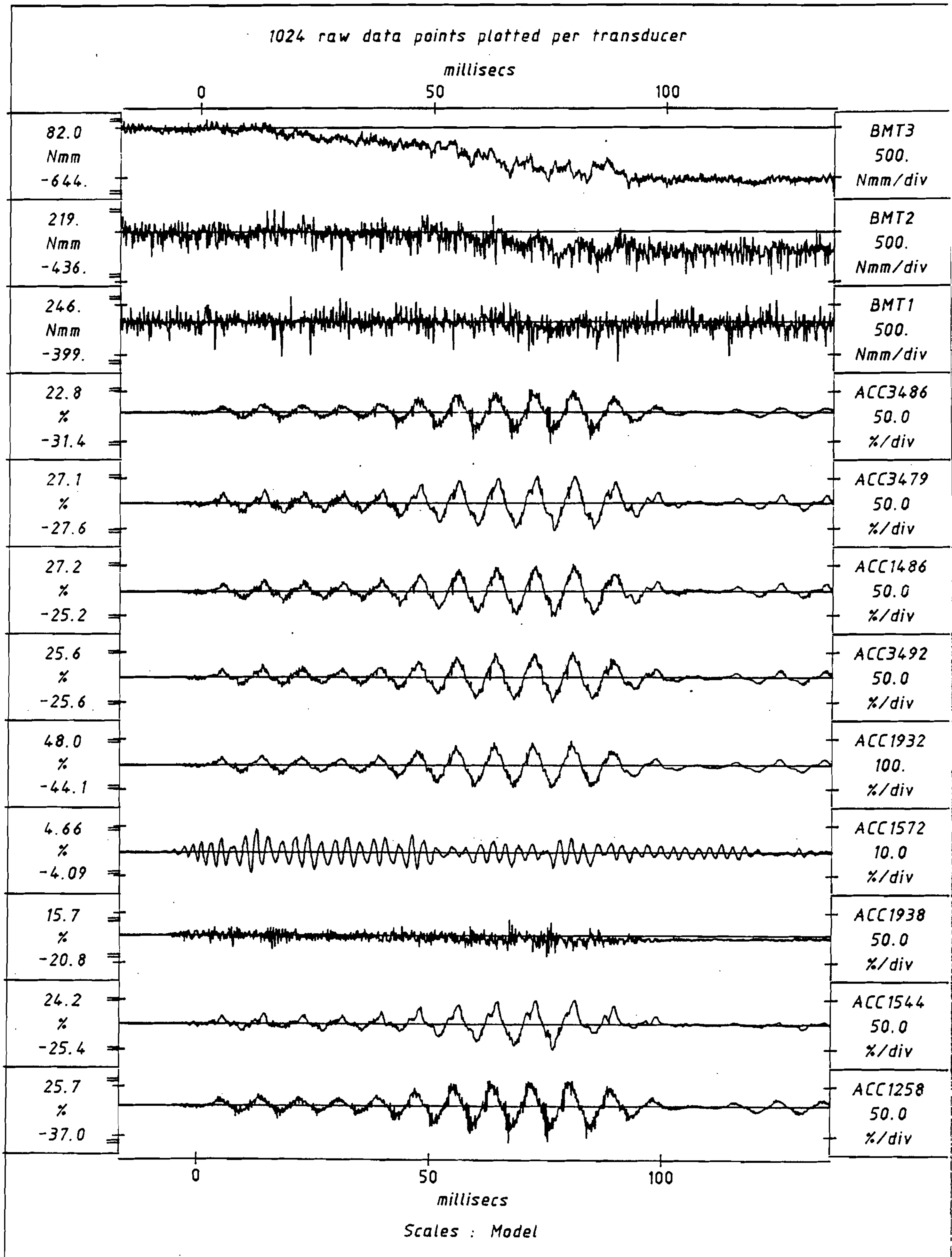
Fig 3.4 Dimensions And Instrumentation For Model AM-3

1024 raw data points plotted per transducer

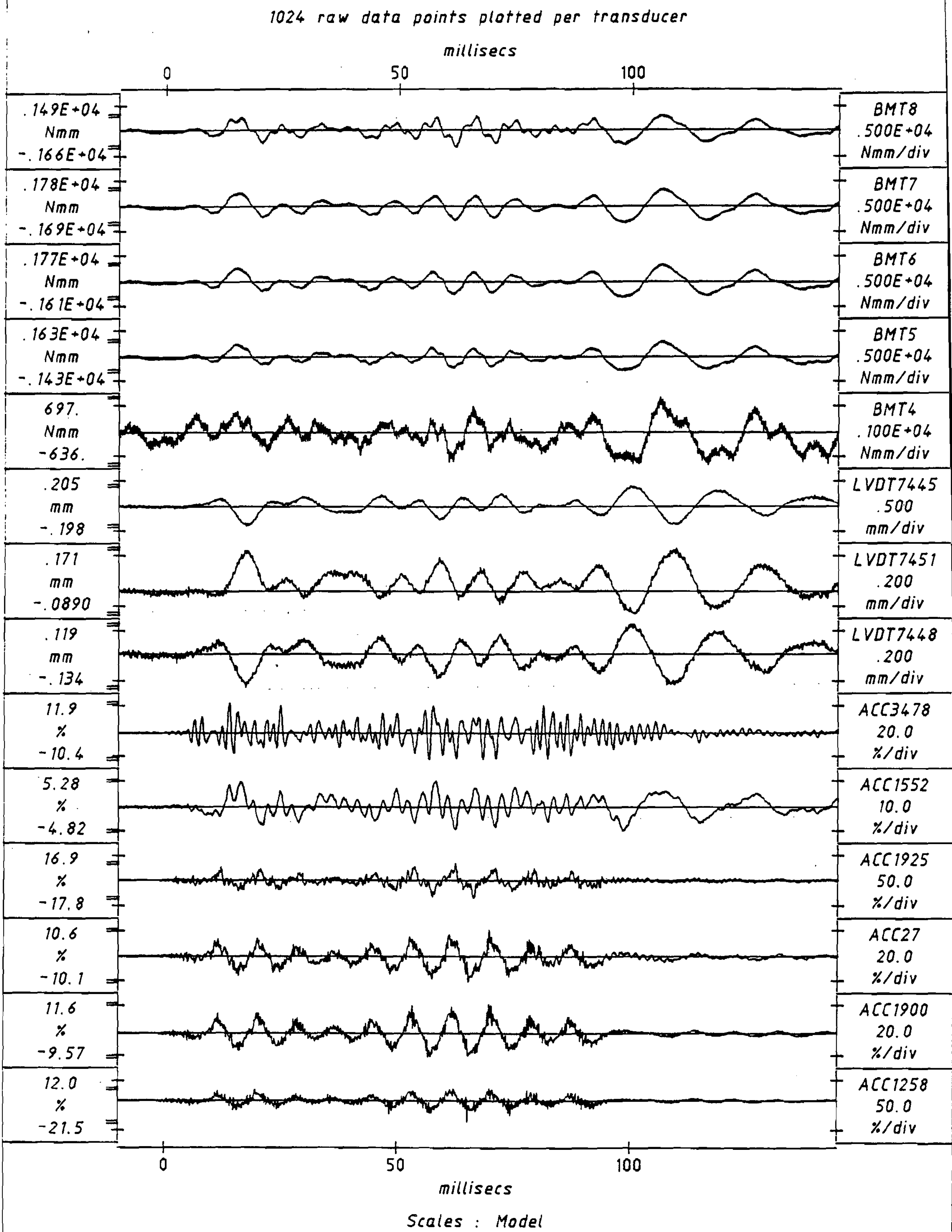


Scales : Model

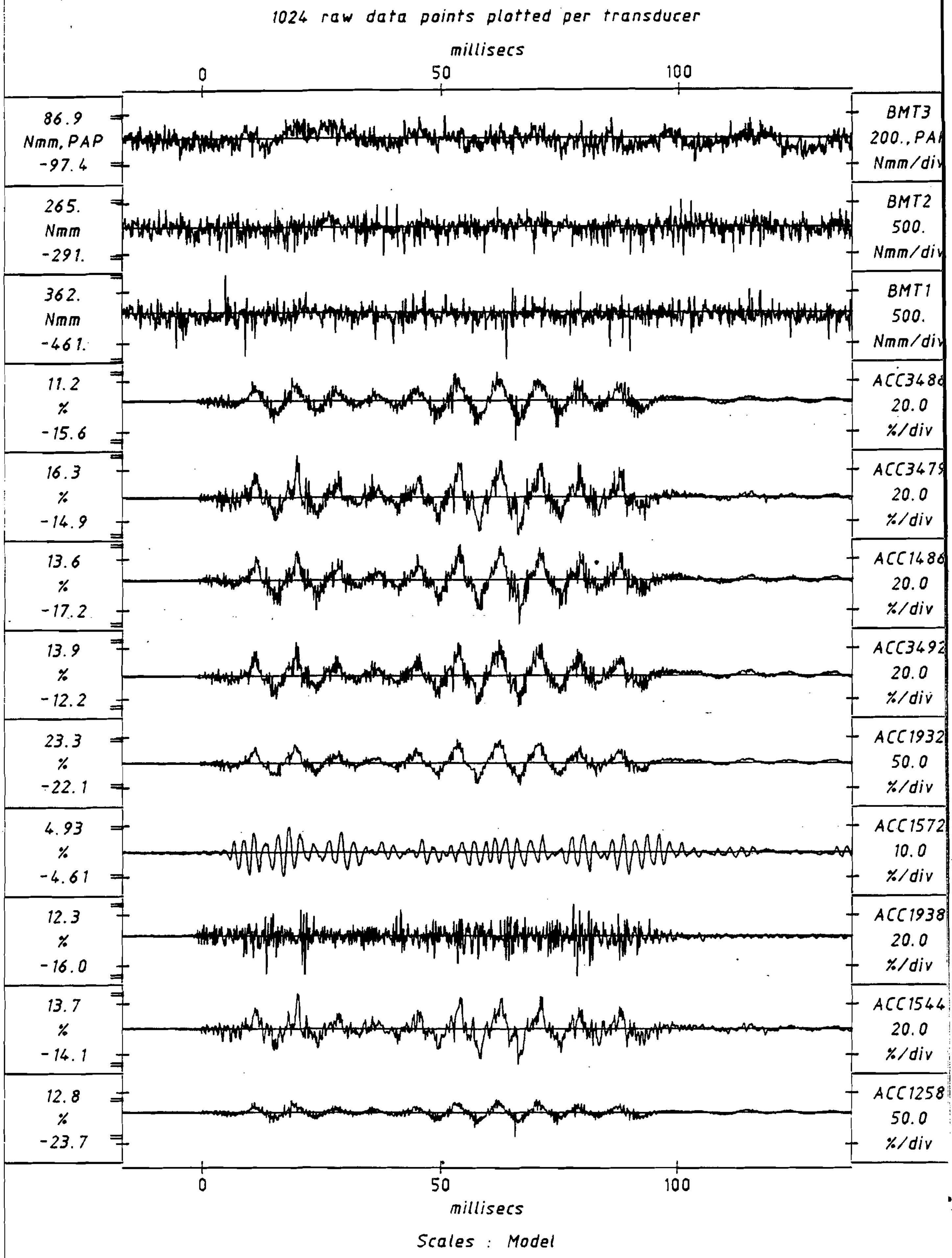
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 77.9g Km = 37.3% Kp = 43.9%	FIG. NO. 3.5(a)



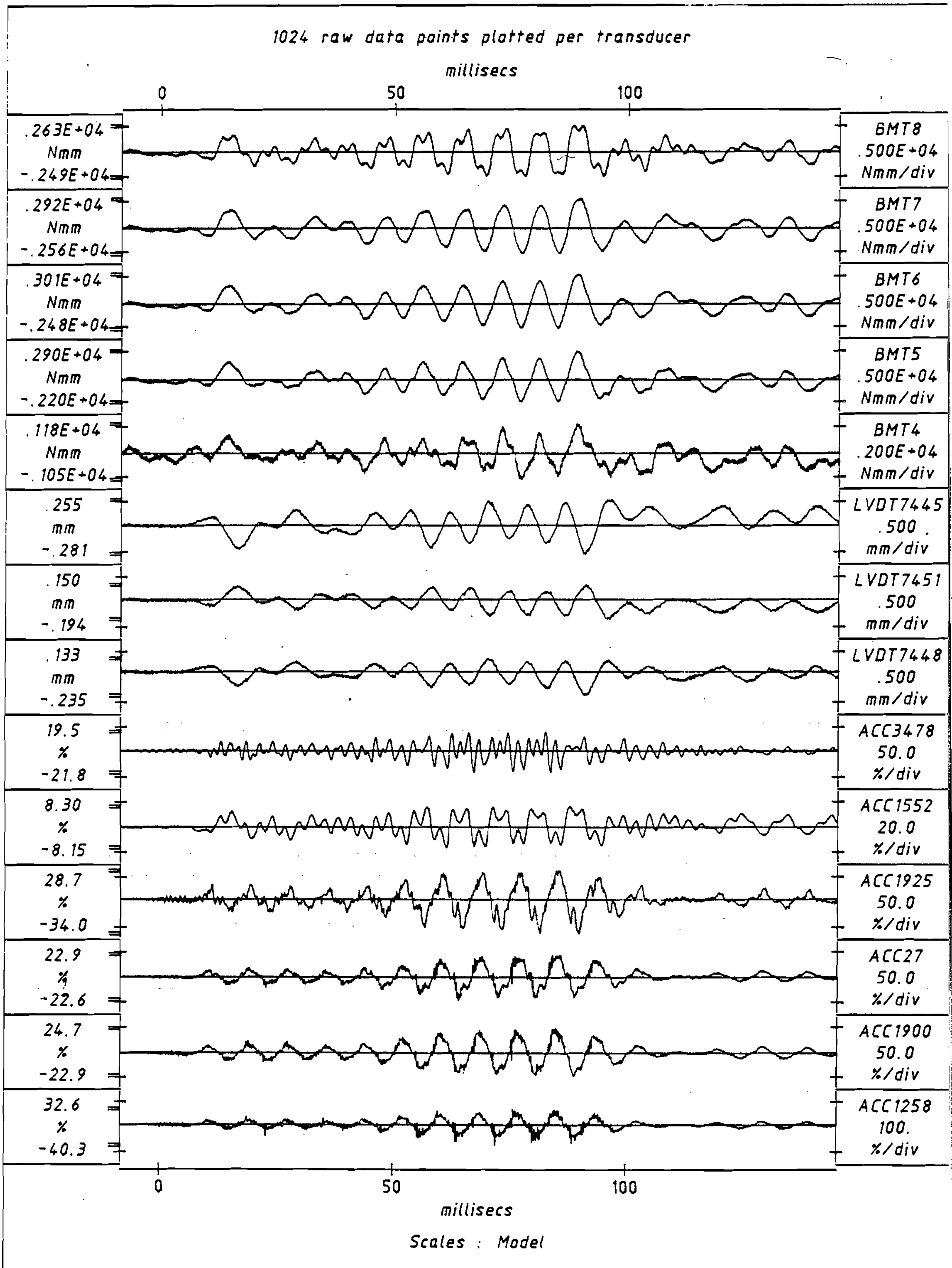
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 77.9g Km = 31.4% Kp = 37.0%	FIG. NO. 3.5(b)



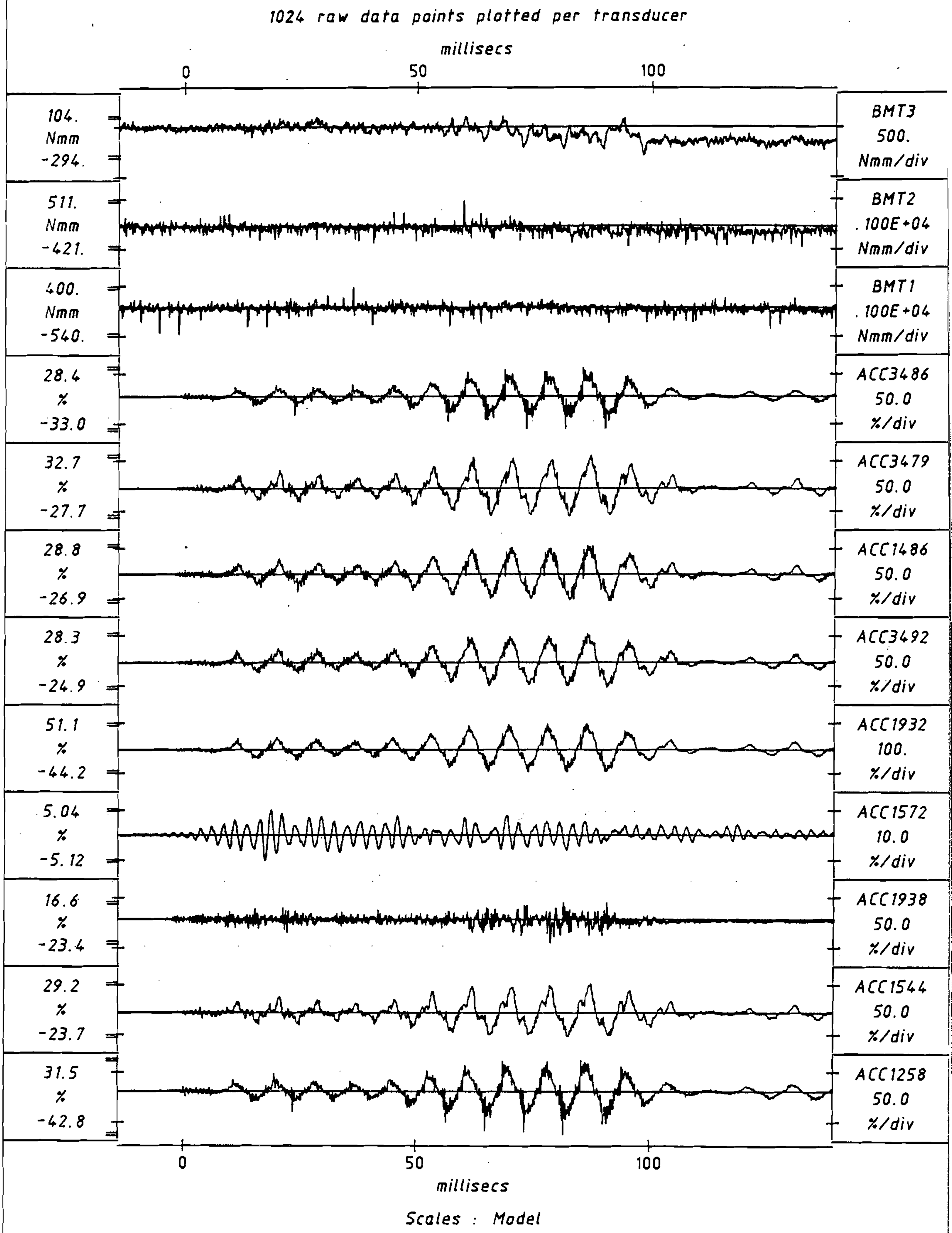
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 77.9g Km = 17.1% Kp = 21.9%	FIG. NO. 3.6(a)



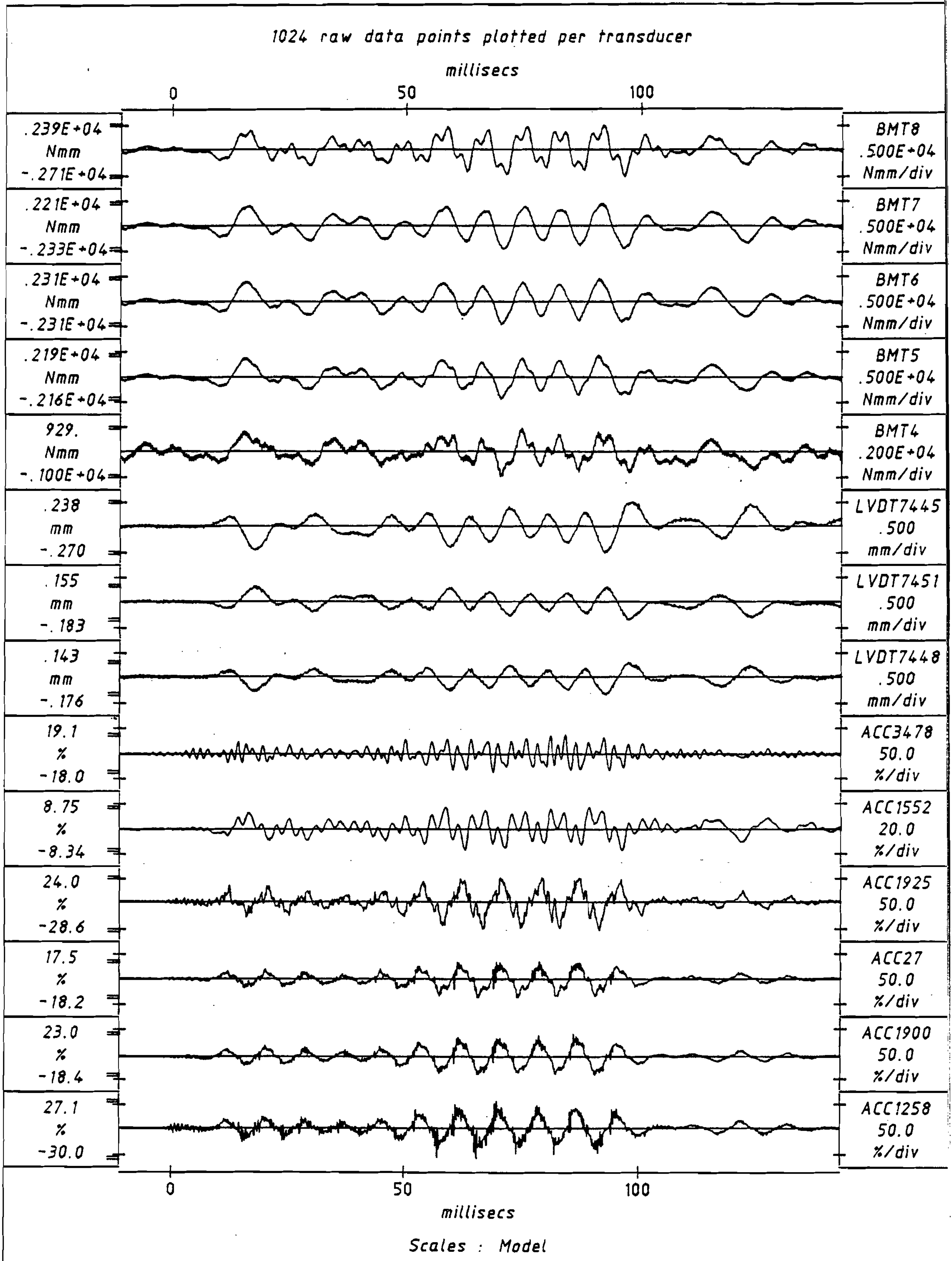
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 77.9g Km = 18.3% Kp = 23.7%	FIG.NC 3.6(b



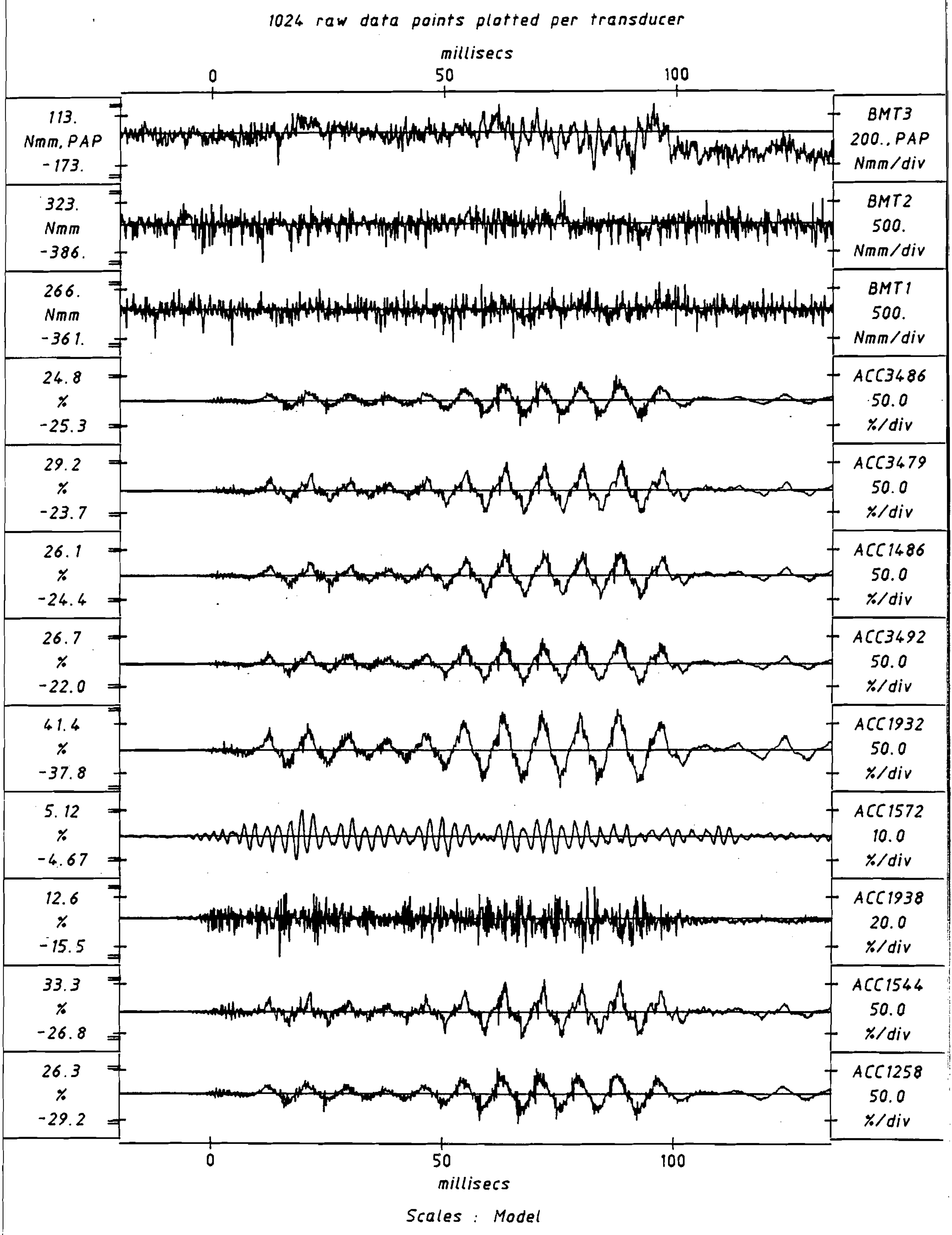
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 77.9g Km = 37.3% Kp = 41.2%	FIG.NO. 3.7(a)



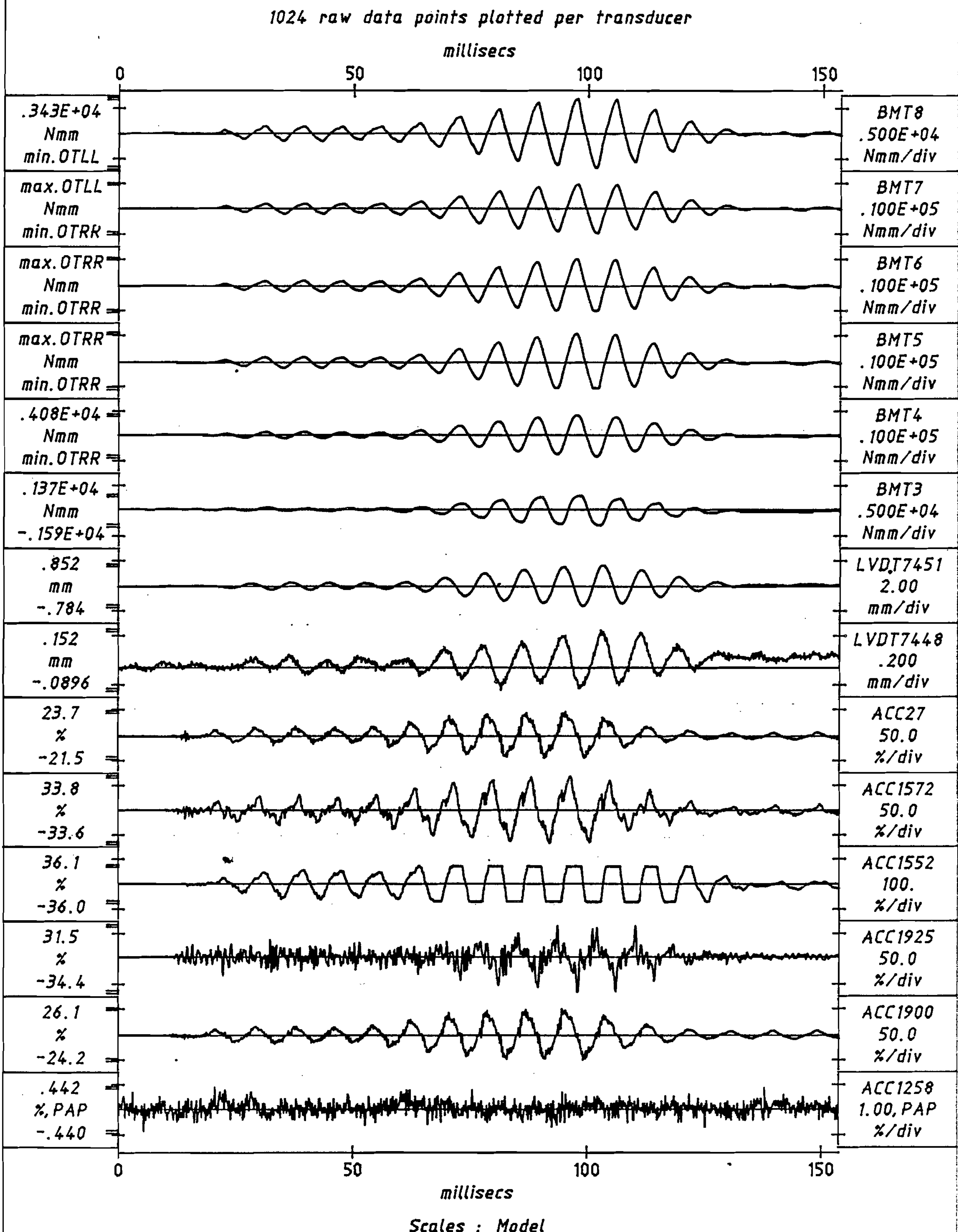
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 77.9g Km = 37.2% Kp = 42.8%	FIG. NO. 3.7(b)



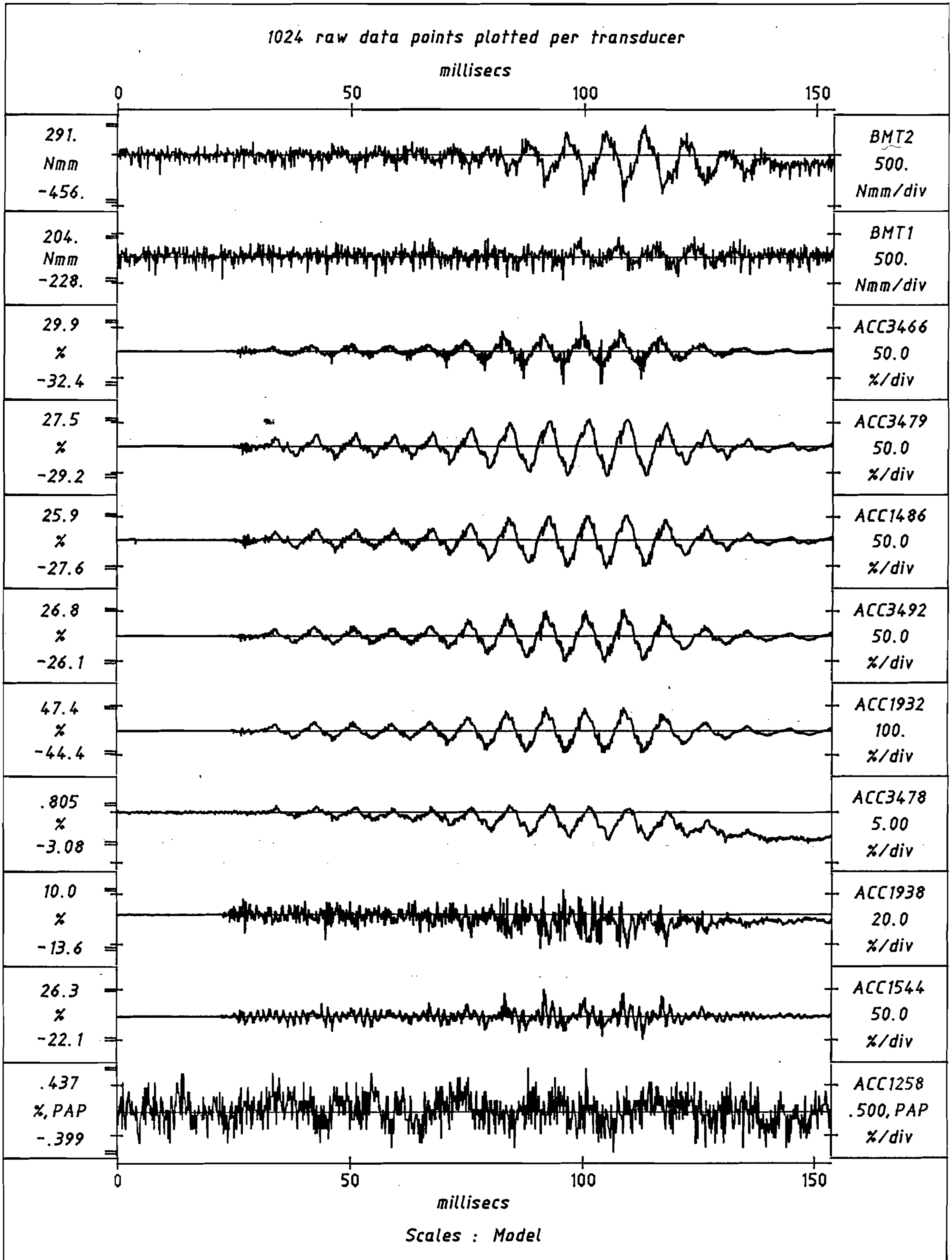
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 77.9g Km = 29.2% Kp = 30.7%	FIG. NO. 3.8(a)



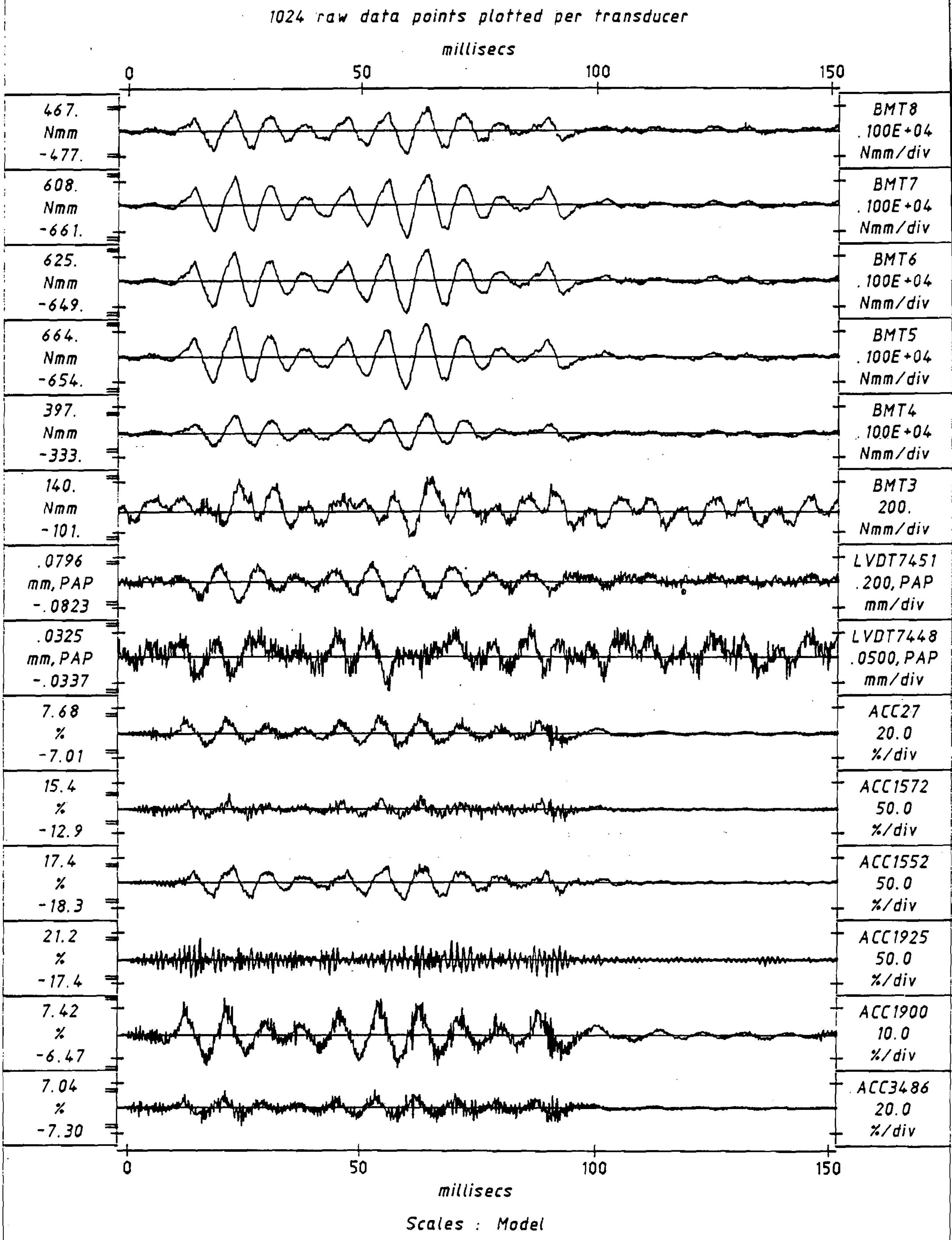
TEST AM-1 MODEL 1 PILE FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 77.9g Km = 27.8% Kp = 29.2%	FIG. NO. 3.8(b)



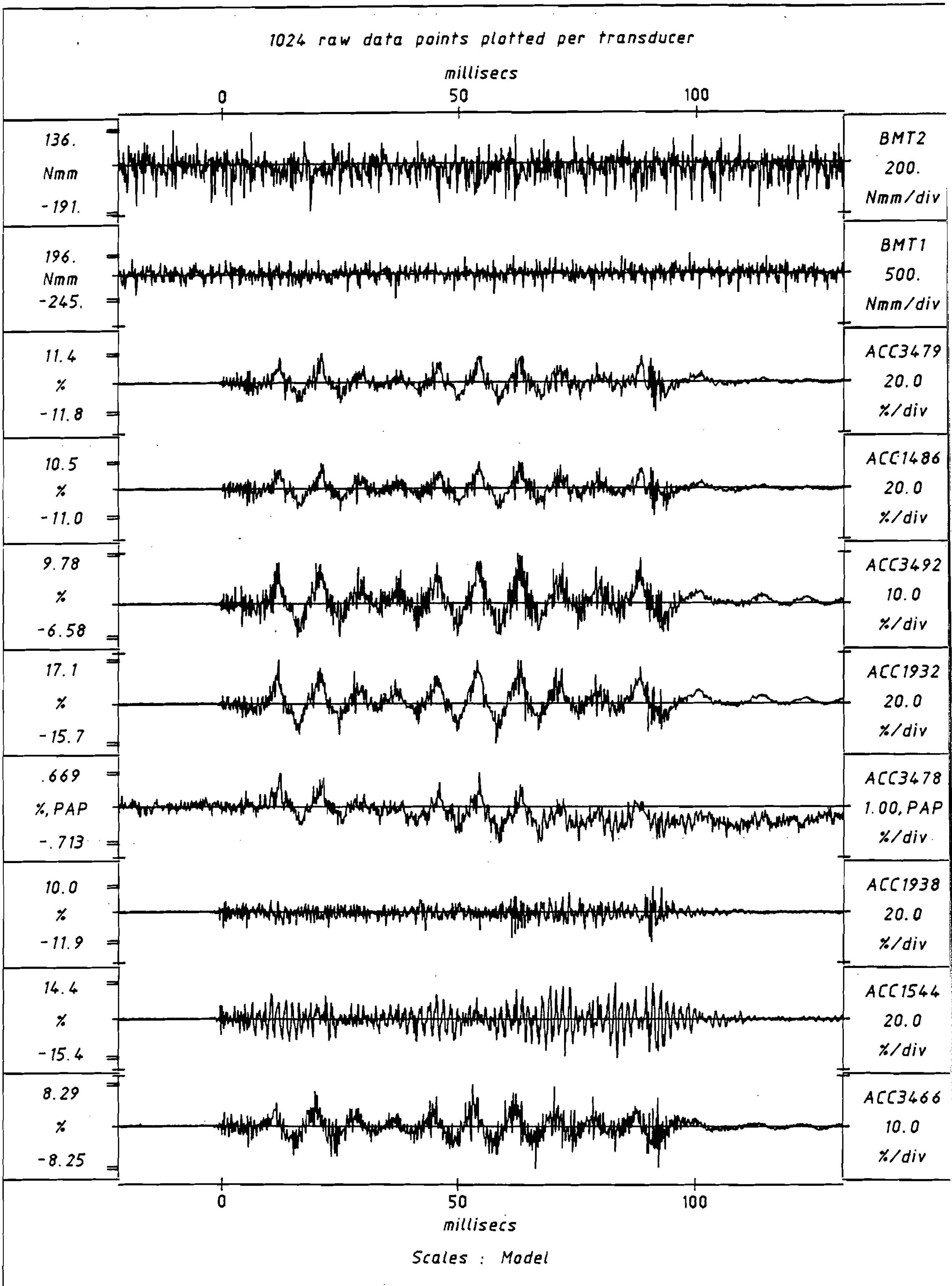
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 77.9g Km = .451% Kp = .452%	FIG. NO. 3.9(a)



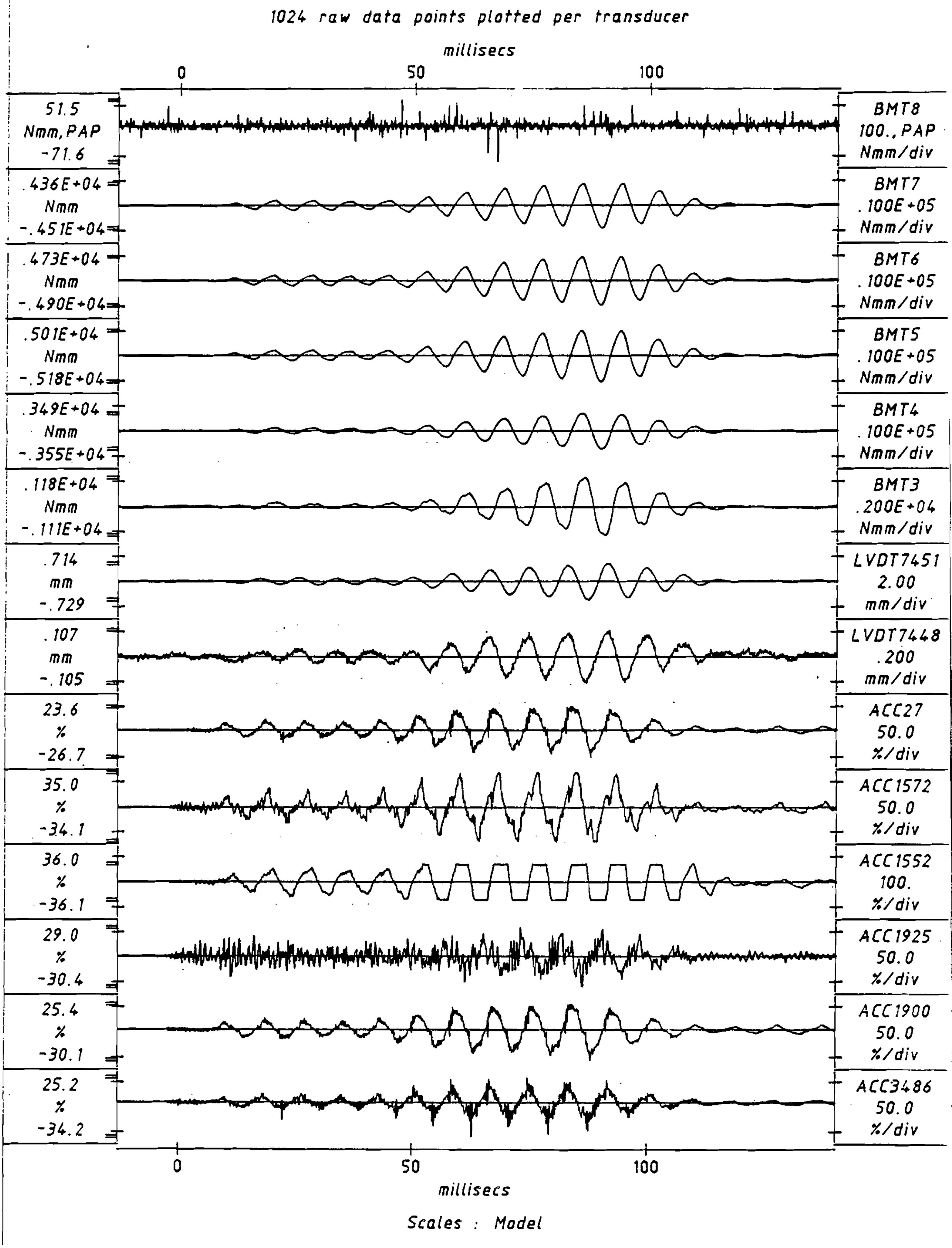
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 77.9g Km = .418% Kp = .437%	FIG. NO. 3.9(b)



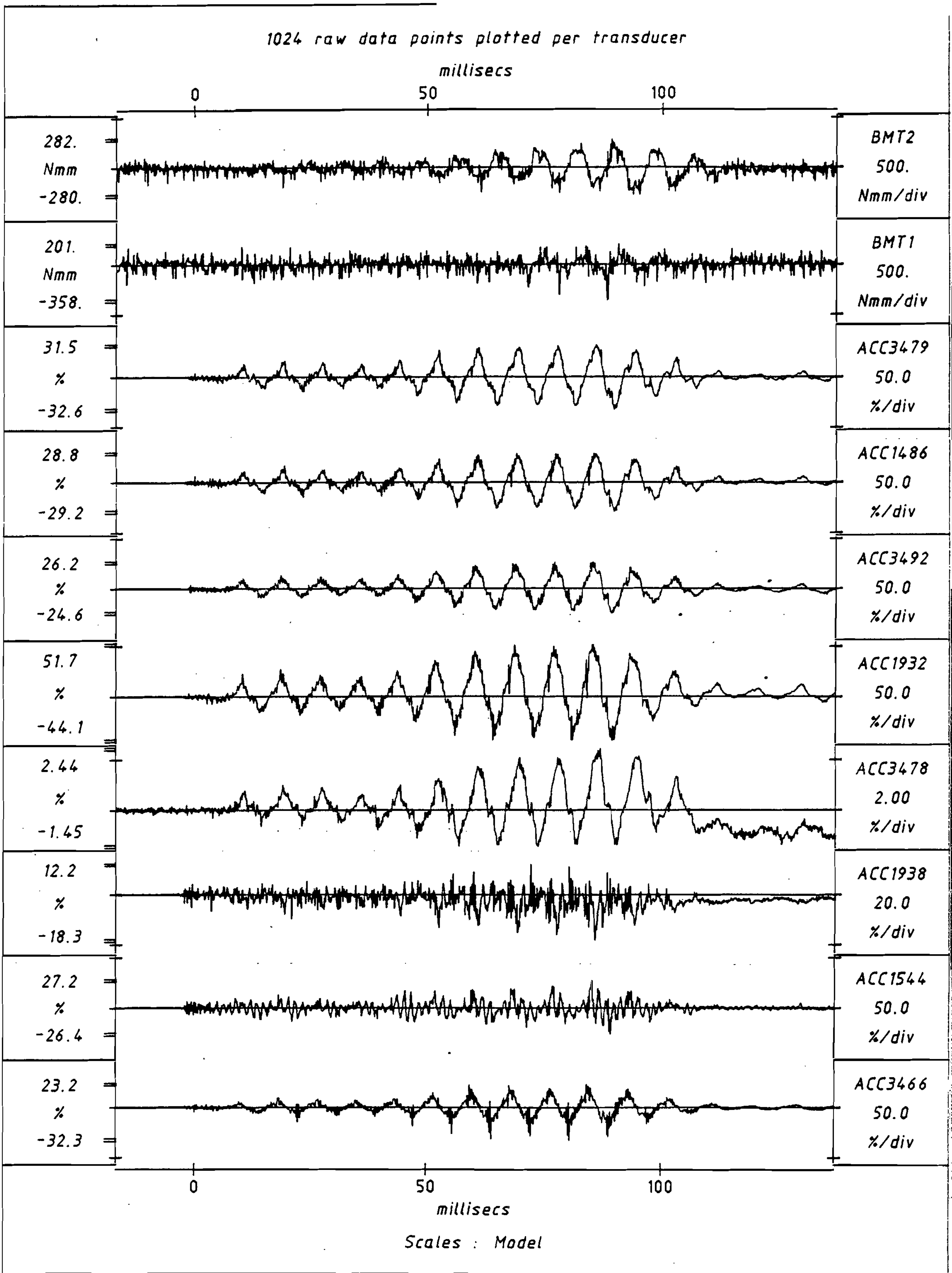
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 77.9g Km = 7.68% Kp = 7.82%	FIG.NO. 3.10(a)



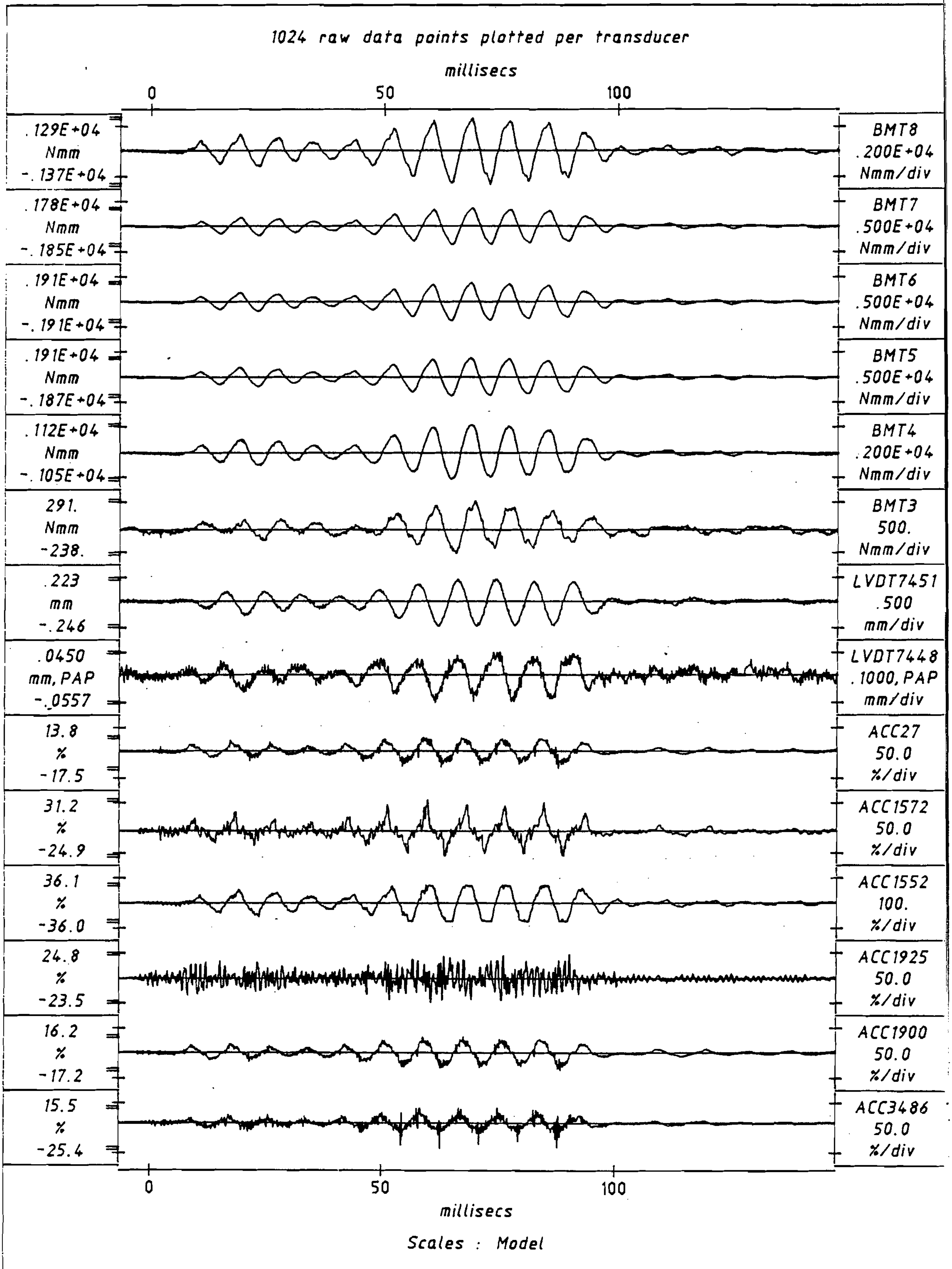
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 77.9g Km = 8.27% Kp = 8.29%	FIG.NO 3.10(b)



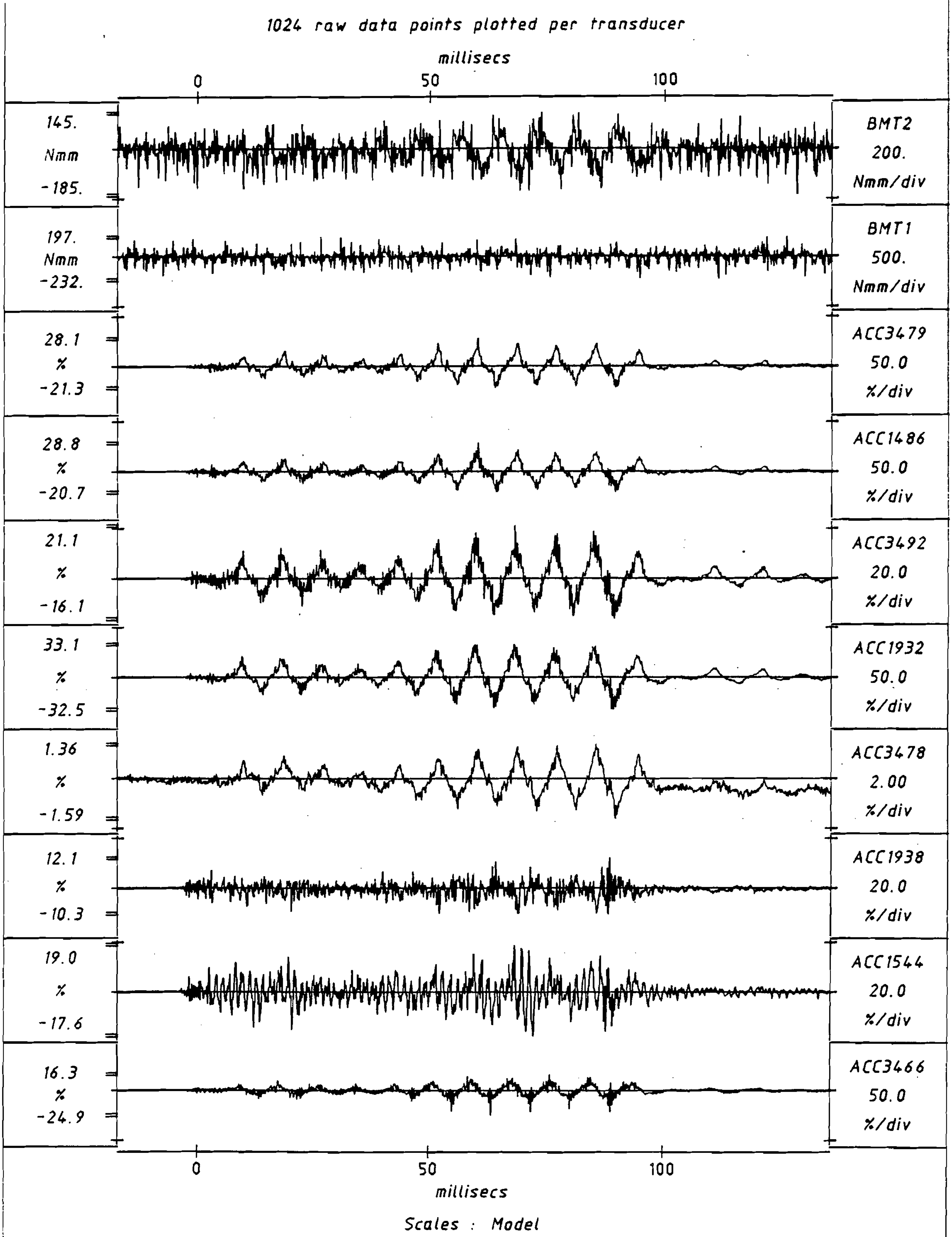
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 77.9g Km = 31.8% Kp = 36.6%	FIG. NO. 3.11(a)



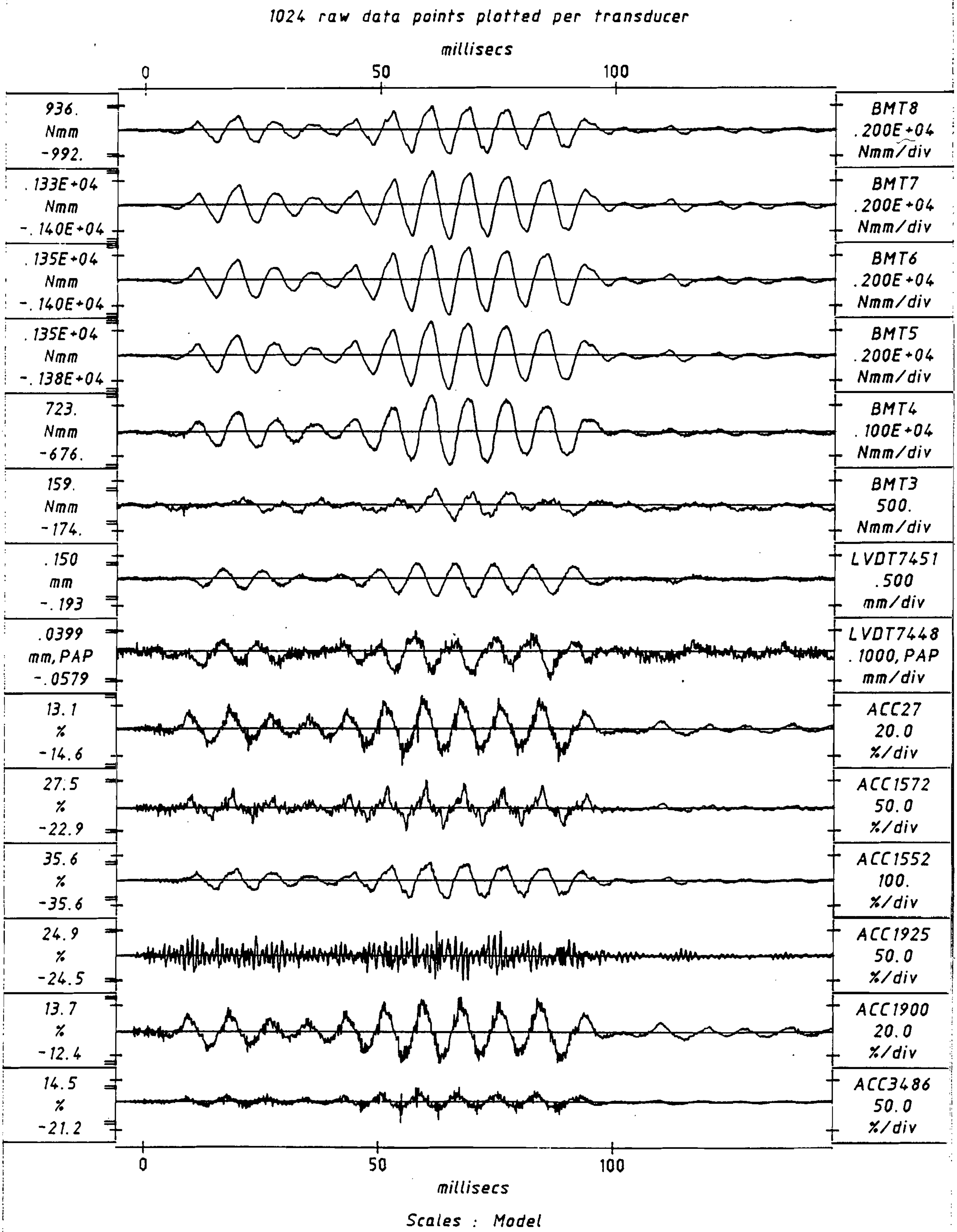
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 77.9g Km = 27.7% Kp = 32.3%	FIG. NO. 3.11(b)



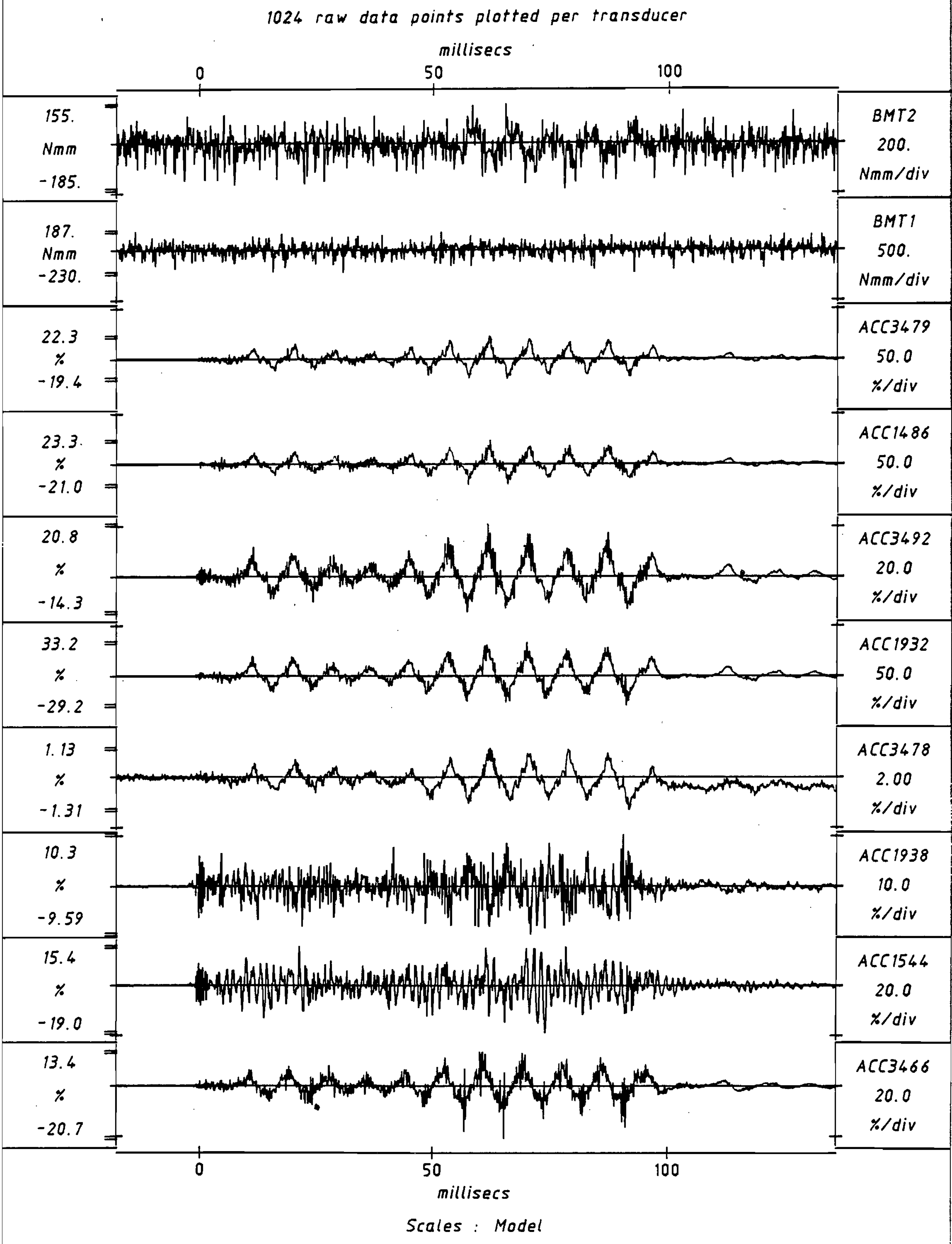
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 77.9g Km = 21.9% Kp = 27.3%	FIG. NO. 3.12(a)



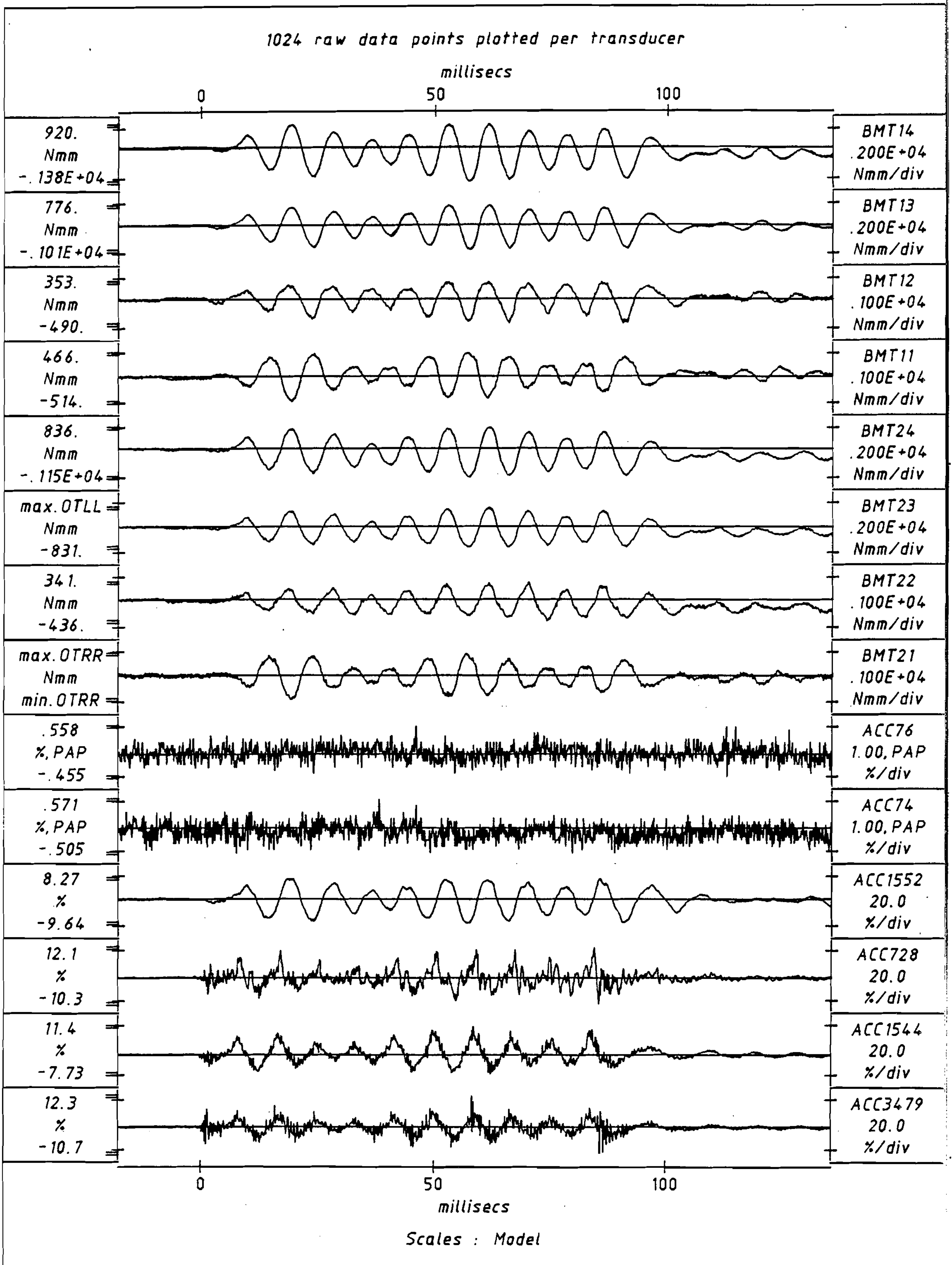
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ4	SHORT-TERM TIME RECORDS	G = 77.9g Km = 20.6% Kp = 24.9%	FIG. NO. 3.12(b)



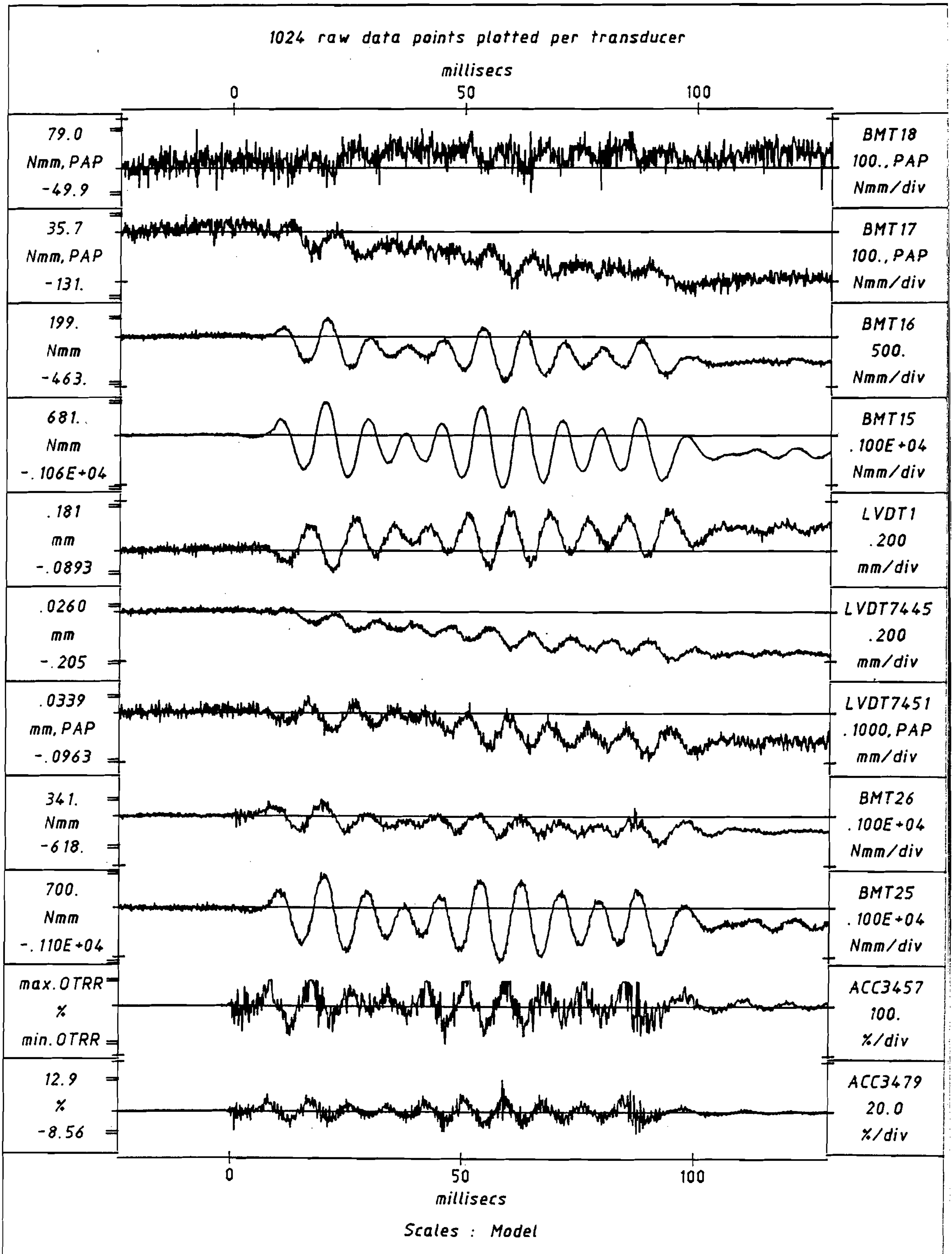
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ5	SHORT-TERM TIME RECORDS	G = 77.9g Km = 19.2% Kp = 22.8%	FIG. NO. 3.13(a)



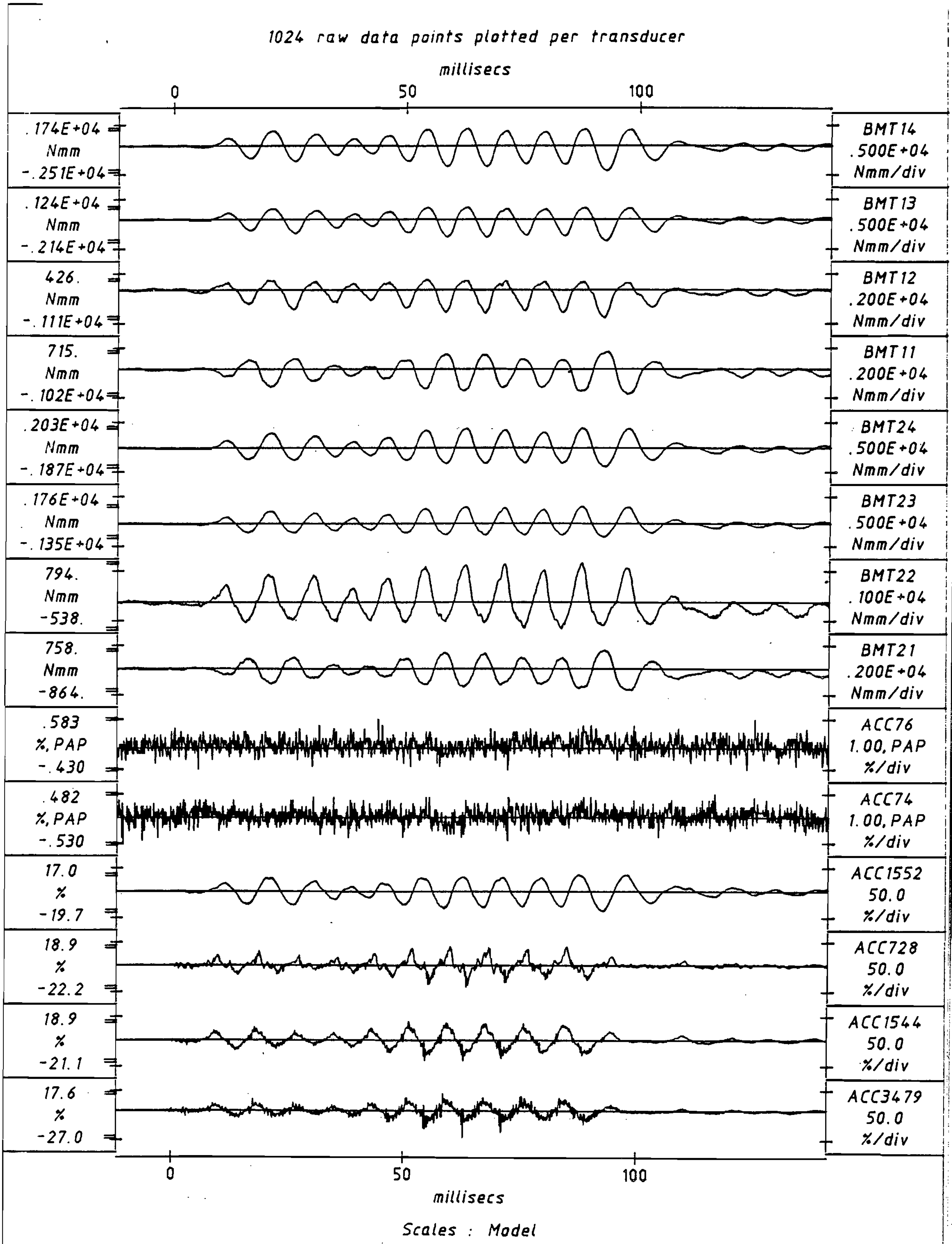
TEST AM-2 MODEL 0 PILE FLIGHT 1	EQ5	SHORT-TERM TIME RECORDS	G = 77.9g Km = 17.1% Kp = 20.7%	FIG. NO. 3.13(b)



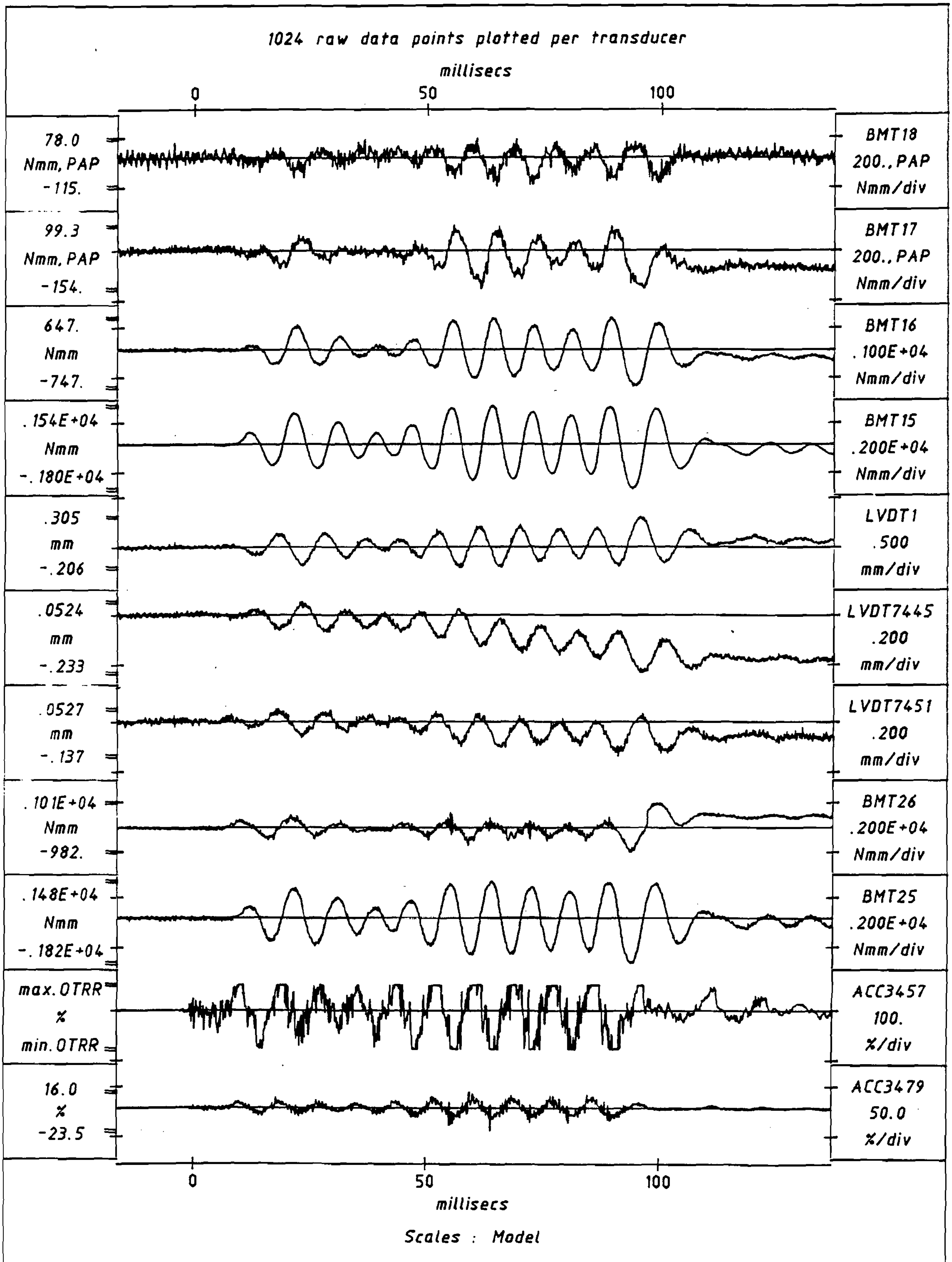
TEST AM3 MODEL PILGR 4 FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 77.9g Km = 11.5% Kp = 12.3%	FIG.NO. 3.14(a)



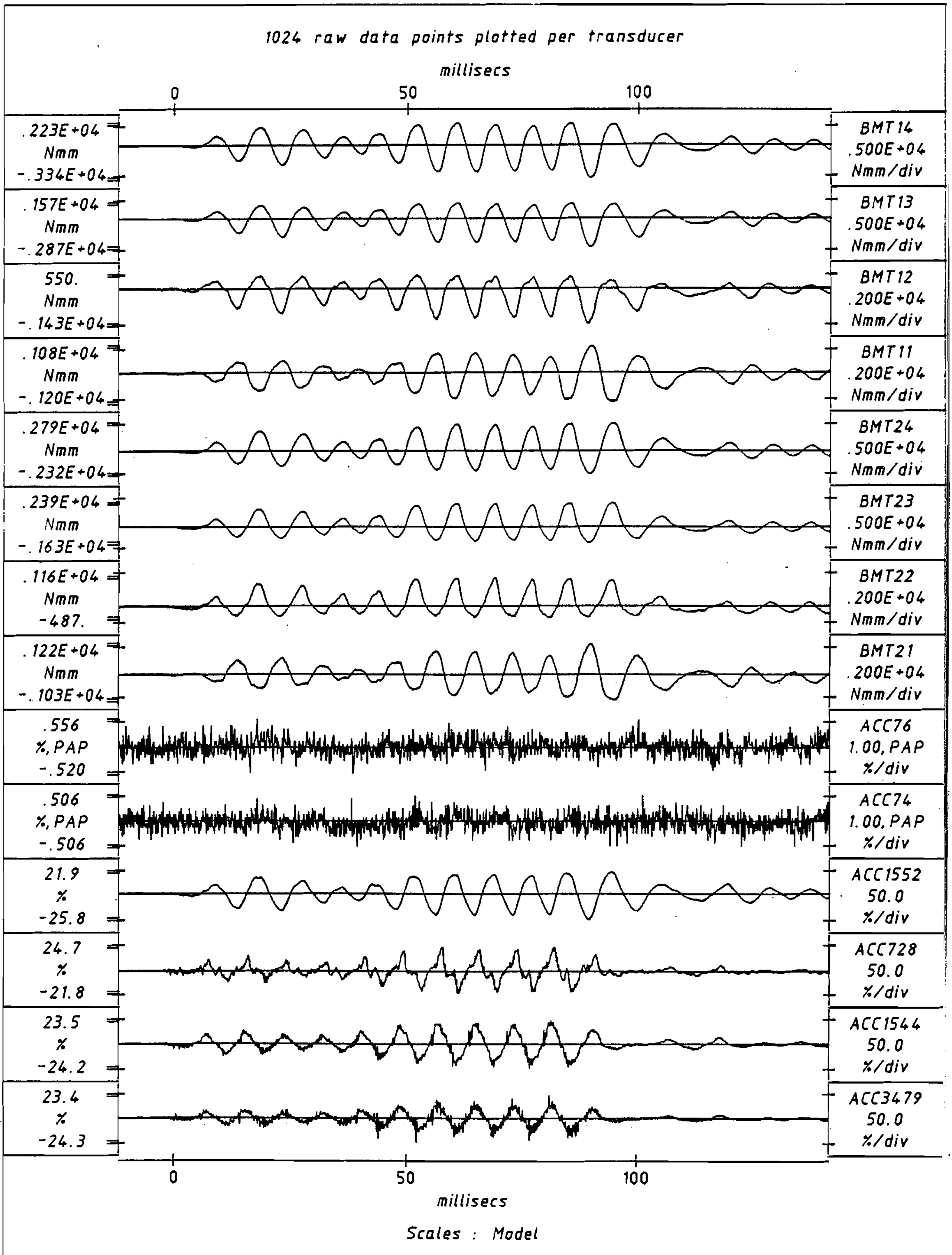
TEST AM-3 MODEL PILGR 4 FLIGHT 1	EQ1	SHORT-TERM TIME RECORDS	G = 77.9g Km = 10.7% Kp = 12.9%	FIG. NO. 3.14(b)



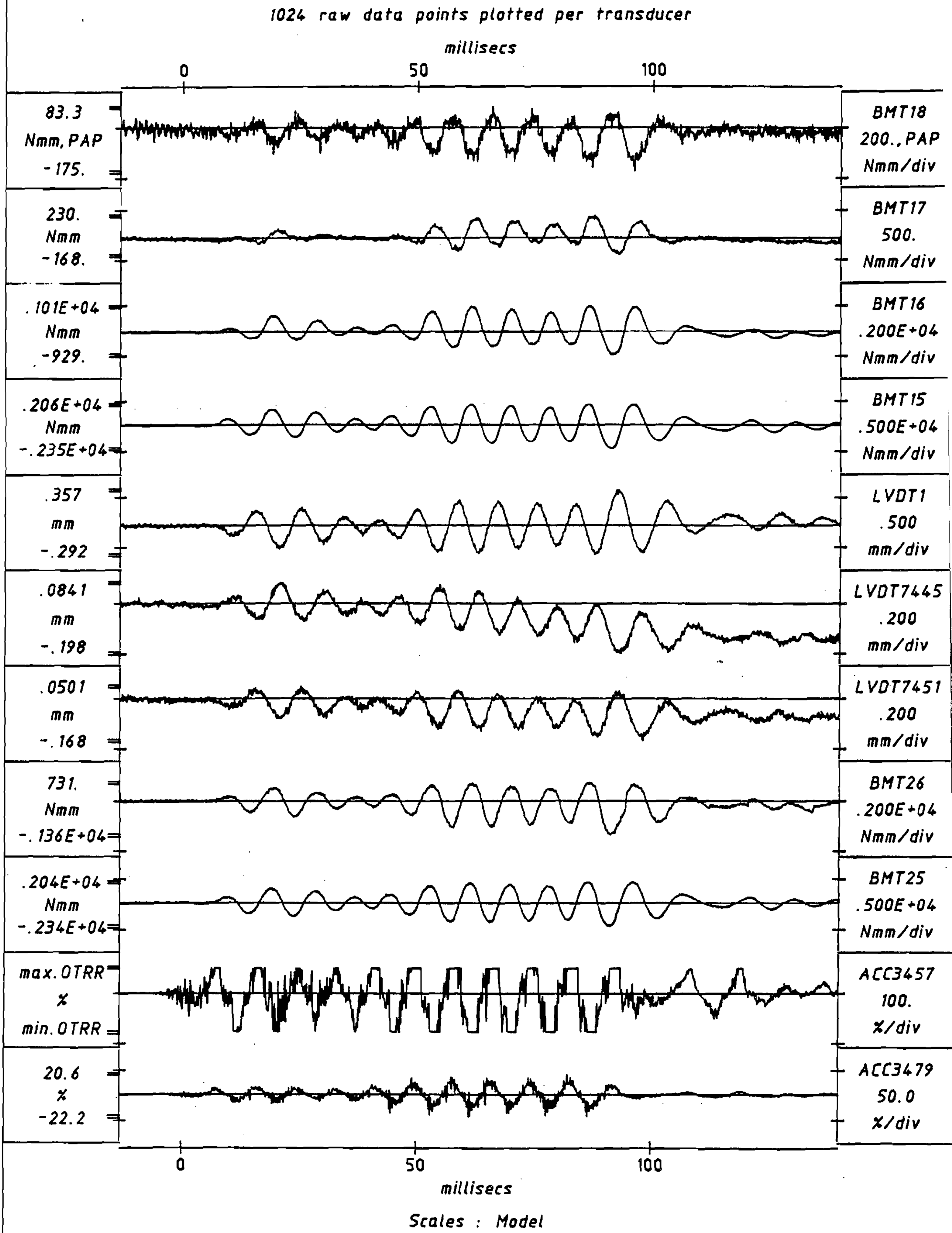
TEST AM3 MODEL PILGR 4 FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 77.9g Km = 22.3% Kp = 27.0%	FIG. NO. 3.15(a)



TEST AM-3 MODEL PILGR 4 FLIGHT 1	EQ2	SHORT-TERM TIME RECORDS	G = 77.9g Km = 19.8% Kp = 23.5%	FIG. NO. 3.15(b)



TEST AM3 MODEL PILGR 4 FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 77.9g Km = 23.8% Kp = 24.3%	FIG.NO. 3.16(a)



TEST AM-3 MODEL PILGR 4 FLIGHT 1	EQ3	SHORT-TERM TIME RECORDS	G = 77.9g Km = 21.4% Kp = 22.2%	FIG. NO. 3.16(b)