Large Scale Modelling of Soil/Pipe Interaction Under Moment Loading

Final Report

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Large Scale Modelling of Soil/Pipe Interaction Under Moment Loading - Final Report

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1.0 SUMMARY

This is the final report associated with the "Large Scale Modelling of Soil/Pipe Interaction Under Moment Loading" project for the Geological Survey of Canada (GSC).

The objective of this project is to assess the flexural behaviour of a pipe buried in dense sand during bending induced by lateral loading up to a limit of 10% pipeline ovalization.

Pipeline bending strain limits have been established in part by considering the bending response of exposed pipelines, Walker and Williams (1995). This response may be moderated in buried pipelines by the restraint of the surrounding soil.

Two tests, designated GSC01 and GSC02, were conducted. The tests and their results are described in the C-CORE reports 98-C20 and 98-C21. During each test, the pipeline longitudinal profile, pipe ovalization, associated soil deformations and pipeline forces under the applied loads were measured. Laboratory test results on the soil used during the program and tensile tests on pipe specimens are presented in C-CORE report 98-C23. In addition to the original workscope, ABAQUS analyses were developed to assist in the interpretation and design of the pipe tests.

This report compares the measured response and failure mode of these buried pipelines subjected to bending to those previously determined from exposed pipelines and other tests.

2.0 PROJECT OVERVIEW

2.1 Objective

The objective of this project is to measure the large strain flexural response of a pipeline subjected to bending when buried in dense sand.

Pipeline bending strains limits have been established in part by considering the bending response of exposed pipelines, Walker and Williams (1995). This response may be moderated in buried pipelines by the restraint of the surrounding soil. This project compared the measured response and failure mode of buried pipelines subjected to bending to those previously determined from exposed pipelines.

2.2 Methodology

A full-scale pipeline-soil interaction test facility was established by C-CORE as described by Paulin et al. (1997). The National Energy Board and the Geological Survey of Canada partially supported C-CORE through the federal PERD (contract 84084-50251/01-XSH) to provide data of the resistance developed by buried rigid pipelines in sand and clay under both lateral and axial loading using this facility. This project extended that contract, and utilised the available facilities, techniques and equipment with minor modification to undertake the work described below.

An instrumented pipeline was buried in compacted dense sand and subjected to bending through lateral loading at the pipe ends. The deflected pipeline profile, pipeline ovalisation and associated soil deformations during pipeline loading were measured. A series of laboratory tests were conducted to determine the soil and pipe coupon properties. These profiles and pipe cross-sections were compared to similar measurements by others to help identify new strain limits for buried pipelines.

2.3 Testing Program

The testing was divided into 5 tasks as outlined below.

Task 1 - Test preparation

The test preparation included reconfiguration of the test tank, modification of the loading actuators and acquisition of the test sand and the pipeline sections. The lateral loading test rig described by Paulin et al. (1997) was modified as described in report 98-C20. The tank was reconfigured to provide a 6m long by 3m wide by 1.4m deep test bed. The two actuators were relocated from the end wall to the side wall of the tank. The tank wall was reinforced in the vicinity of the actuators to carry the reaction load. The loading arms were replaced to accommodate pipe displacements larger than the fixed stroke of the actuator system.

About 50 tons of sand was required to fill the enlarged test bed. Locally available moist bulk sand was used for this testing program. This sand was selected to have similar shear strength properties to that used in the previous test program. Two 5m long 0.203m diameter pipes were acquired for the test program.

Existing surface profiling systems and displacement transducers were used to periodically monitor surface displacements of the sand bed during pipe displacement. Instrumentation was also placed within the sand bed to monitor internal soil deformations. Density and penetration resistance profiles were assessed throughout the test bed before and after the pipe loading test.

Task 2 - Pipe Instrumentation

Pipe instrumentation comprised two load cells, three displacement transducers, ten curvature sensors, sets of strain gauges and three ovalisation sensors. The load-displacement response of each pipe end during loading was monitored using the existing load cells and displacement transducers. A third displacement transducer monitored the displacement of the midpoint of the pipe. Ten curvature sensors were mounted inside the pipe. Sets of strain gauges were mounted on the pipe to measure axial and bending strains. Three pairs of displacement transducers were mounted orthogonal to each other at 3 locations close to the mid-length of the pipe to monitor pipeline ovalisation. Circuitry was installed in the pipe to energise the curvature, strain gauge and ovalisation sensors, condition their outputs and interface these outputs to the existing data acquisition system.

Attachment points were added close to the ends of the pipe for the application of the load. The pipe ends were closed with flexible covers to minimise the transmission of axial forces into the pipeline.

Task 3 - Conduct of Flexural Pipeline Tests

Two flexural pipeline tests, designated GSC01 and GSC02, were conducted as described in reports 98-C20 and 98-C21using a test set up similar to that described by Paulin et al. (1997). The pipelines used in these experiments are defined in the Table 1. In each test the instrumented pipe segment was buried in compacted dense sand of known and controlled density. The ends of the pipeline were displaced using the procedures and equipment developed previously. After each 100mm or so of displacement, the pipeline was held in position, the actuators were unloaded, the attachment point to each loading arm was changed and the load reapplied. Particular attention was paid to the measurement of the deflected profile and ovalisation of the pipeline. Translation of the pipe was indicated by the pipe displacement transducer mounted at mid-length of the pipe. The data from each pipe test were analysed and forwarded as reports 98-C20 and 98-C21.

Table 1 GSC Pipeline Parameters

Parameter	GSC01	GSC02
Overall Length (mm)	5814	5690
Nominal Outside Diameter, D_o	8" (203.2 mm)	8" (203.2 mm)
Nominal Wall Thickness, t	1/8" (3.175 mm)	3/16" (4.763 mm)
Material	1010 Carbon Steel	1018 Carbon Steel
Bending Strain Gauge Model #	EA-06-250PD-350	EA-06-250PD-350
Axial Strain Gauge Model #	CEA-06-125UT-350	CEA-06-125UT-350
Yield Strength[1] (MPa)	294	375

1. Yield strength was determined in accordance with ASTM E8-96.

Task 4 - Laboratory Testing
Laboratory testing was performed to determine the shear properties of the sand and the stress-strain tensile response of pipeline coupons. The sand shear properties were determined using a direct shear box with sand samples under different stress levels. The grading and maximum and minimum densities of the sand were also determined. The results of the tests were forwarded as the third report 98-C23 on completion of the task.

Task 5 - Data Analysis & Reporting
The data from the pipeline tests were analysed. The response of the buried pipeline under flexure was compared with that described in the literature for exposed pipelines. This comparative assessment is described below in this final report. Raw and processed data from the test series are available to GSC in a format to be agreed upon.

3.0 DISCUSSION & CONCLUSIONS

The results of test GSC01 are presented in report 98-C20. It was expected that a plastic hinge might develop at the midlength of this pipeline. The pipeline was instrumented accordingly, Figure 2 of report 98-C20. Plastic hinges, however, formed about 1.2m from each end of the pipe. These hinges developed into buckles with more than 14% ovalisation of the pipe local to each buckle, Table 5 of report 98-C20. This test achieved the first objective of the project which was to obtain 10% pipe ovalisation of a buried pipe. However, the instrumentation in the vicinity of these buckles was very limited. There were no ovalisation sensors in these vicinities. The 3 sets of ovalisation sensors were located at the pipe centreline and at the locations of bend sensors 4 and 5, Figure 2. A maximum of 0.27% pipe ovalisation was measured at these locations, Figure 21b in 98-C20, after 140mm of pipe end displacement.

These pipe ovalisation measurements can be compared to associated lateral pipe bending strains. These bending strains, close to the location of the ovalisation sensors, are assessed from the pipe bend sensors in the absence of strain gauge data at these locations. The deflected angle, ϕ between reference points A and B in the pipe, a distance L apart, is measured by the bend sensor located between these 2 points, Figure 1. The average radius of curvature, R between these 2 points can be determined directly from these 2 measurements as shown in the figure for small deflection angles. Standard bending theory can then be used to assess the average maximum bending strain:

$$\varepsilon_b = D_o / 2R \cong D_o \phi / L,$$ where D_o is the pipe diameter.

This strain determination was validated against adjacent bend sensor and strain gauge bending strain measurements in both tests GSC01 and GSC02 as shown for example in Figure 2. The associated instrumentation positions are shown in Figure 2 of report 98-C20. A line of equal bending strain is plotted in the figure for ease of comparison. There is a good comparision between the 2 measurement techniques up to 1500$\mu\varepsilon$, especially considering the bend sensor and strain gauge measurements are spatially averaged and spot values respectively and the measurement positions do not coincide. After 1500$\mu\varepsilon$ the bend sensor response is strongly influenced by the adjacent plastic hinge development.

The 3 sets of pipe ovalisation measurements for test GSC01 are compared to adjacent lateral pipe bending strains in Figures 3 to 5. The pipe ovalisation at the end of the test, that is the final points in the traces, correspond well with the manual pipe ovalisation measurements made after excavation of the pipe, as presented in Table 5 of report 98-C20. The maximum pipe ovalisation occurs after 110 to 140 mm of pipe displacement, Figure 21 of report 98-C20.

BS 8010 (1993) states that pipe ovalisation, f due to bending strain, ε_b can be calculated as follows:

$$f = (D_{max} - D_{min}) / (D_{max} + D_{min}) = C_p \{ C_f (\varepsilon_b * D_o/t)^2 + f_o)$$

where $C_f = 0.06 [1 + D_o/(120t)]$
$C_p = 1/(1 - P/P_e)$, pressure magnification factor, taken as unity
f_o = initial ovalisation
$P = P_o - P_i$ = external less internal pipe pressure
$P_e = 2E/(1-v^2) * (t/D_o)^3$, critical pressure

Walker and Williams (1995) present measurements that show this formula gives a reasonable prediction of ovalisation for bending strains up to 1% to 2%. The BS8010 prediction of pipe ovalisation due solely to bending strain for test GSC01 is superimposed in Figures 3 to 5. It was anticipated that this prediction would overestimate pipe ovalisation due to bending in buried pipelines. This was not the case. The pipe ovalisation measured traces are significantly higher than the predicted one and of the opposite curvature during loading.

This indicates that another mechanism is more strongly controlling the measured pipe ovalisation at these ovalisation levels. Pipe ovalisation will also result from the the effect of the increased lateral soil pressure. Ovalisation due to soil pressure can be estimated using the modified Iowa formula after Moser (1990):

$$f = \Delta X/ D_o = D_L K W_c D_o^2 / (8EI + 0.061 E' D_o^3)$$

where ΔX = pipe diametral change
D_L = deflection lag factor, assume 1.5
K = bedding constant, assume 0.1
W_c = 'Load' per unit length of pipe, taken as P_u
D_o = mean diameter of pipe
E = pipe modulus of elasticity
I = pipe moment of inertia / unit length, $t^3/12$
E' = soil reaction modulus, taken as 13.8MPa (2000psi)

This modified Iowa formula was shown, for example, by Sargand *et al.* (1994) to reasonably predict the diametral response of a buried HDPE pipe subject to surface loading.

In the analysis of test GSC01, the ultimate lateral soil pressure, P_u on the pipe was assumed to be 96.4kN/m. This pressure would cause a pipe ovalisation of about 5%, which is a typical design limit against pipe curvature reversals and pipe instability. The FE analysis of test GSC01 indicates a mobilised lateral soil pressure at the pipe centreline of about $-0.3P_u$, Figure 36 of report 98-C20. This mobilised pressure would cause about 1.5% pipe ovalisation, which exceeds the measured ovalisation values.

The results of test GSC01 therefore indicate that the observed pipe ovalisation was due primarily to the effect of lateral soil pressure, and not pipe bending strains. The overall pipe flexural response for test GSC01 was assessed after the test using an ABAQUS beam-column type finite element analysis.

Maximum pipe loads and the location of the plastic hinges were reasonably well predicted. Measured displacements to maximum load were consistent with the predicted displacements to initial yielding. The validated ABAQUS analysis was used to design test GSC02 to achieve the formation and development of a plastic hinge at the pipe centreline.

The results of test GSC02 are presented in report 98-C21. The pipeline was instrumented as shown in Figure 1 of report 98-C21. A plastic hinge formed at the centreline, but limited soil resistance in this location prevented the development of significant pipe ovalisation. After about 50mm of pipe end displacement the pipe began to translate through the soil. Surcharging the soil surface temporarily prevented this. The pipe translation recommenced at a pipe end displacement of about 170mm. The hinge developed to about 1.2% ovalisation, but did not form into a buckle. This test achieved the objective of forming a hinge at a controlled location, namely the pipe centreline.

The 4 bend sensor mounts close to the pipe centreline were observed to have detached from the pipe after the test. The 3 sets of ovalisation sensors were attached to 3 of these mounts. The bend sensor responses at the detached mounts were not consistent with those from the attached mounts, Figure 17 of report 98-C21. The ovalisation sensor output is therefore also suspect, especially that from LVDT 5, Figure 20 of that report. The measured pipe ovalisations at the pipe centreline and at bend sensor 6 are shown in Figures 6 and 7 against the adjacent bending strain data from strain gauges. The pipe ovalisation is plotted up to the limit of the strain gauge response. The pipe ovalisation measured traces again appear to be significantly higher than that predicted by BS8010 (1993) and of the opposite curvature during loading.

The pipe ovalisation is plotted against central pipe displacement in Figure 8. The ovalisation values at the end of the traces are similar to those measured manually after the pipe was excavated, Table 6 of report 98-C21. This increases confidence in the suspect pipe ovalisation data. The surcharge was placed after about 25mm of central pipe displacement. The initial ultimate soil resistance, P_u at the pipe centreleine was estimated to be 28 kN/m. This gives a pipe ovalisation due to soil pressure of about 0.9%, after Moser (1990). This predicted pipe ovalisation is close to that measured.

In conclusion, the project objectives were achieved in the 2 tests, however not concurrently. A plastic hinge was developed to more than 10% ovalisation, and a plastic hinge was developed in a predetermined location, namely at the pipe midlength. Sufficient experience has been gained to be reasonably confident of achieving both of these objectives concurrently in any future tests.

It is considered that the pipe ovalisation at the location of the ovalisation sensors was caused primarily by soil pressure and not by the pipe bending strains. The pipe ovalisation due to soil pressure is limited to about 1% by the ultimate soil resistance, P_u. Pipe ovalisation due to pipe bending strains can exceed this value and could therefore be identified in any future tests.

The ABAQUS beam-type analyses provided a reasonable prediction of the observed overall pipe flexural response. These analyses will be developed and discussed further after an experimental program for the Minerals Management Service (MMS) has concluded later this fiscal year. This program will provide measured P-Y curves for the pipe and soil conditions discussed in this report. The GSC will have access to the MMS reports through a previously agreed exchange of project reports. The current ABAQUS beam-type model is however not capable of capturing ovalisation of the pipeline. A more sophisticated continuum model is required to capture pipe ovalisation due to soil pressure and pipe bending strain.

Some photographs taken during different stages of the testing program are included at the end of this report as photos A-H. These photos show the pipeline array as well as the ovalisation sensors, the post-test pipe profile from both tests, and the pre and post-test testbed surface from GSC02.

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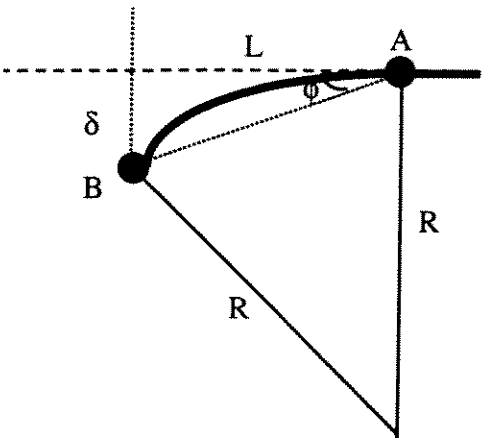

$R = L\ (\phi + 1/\ \phi)\ /2\ \cong\ L/2\phi$, for small ϕ

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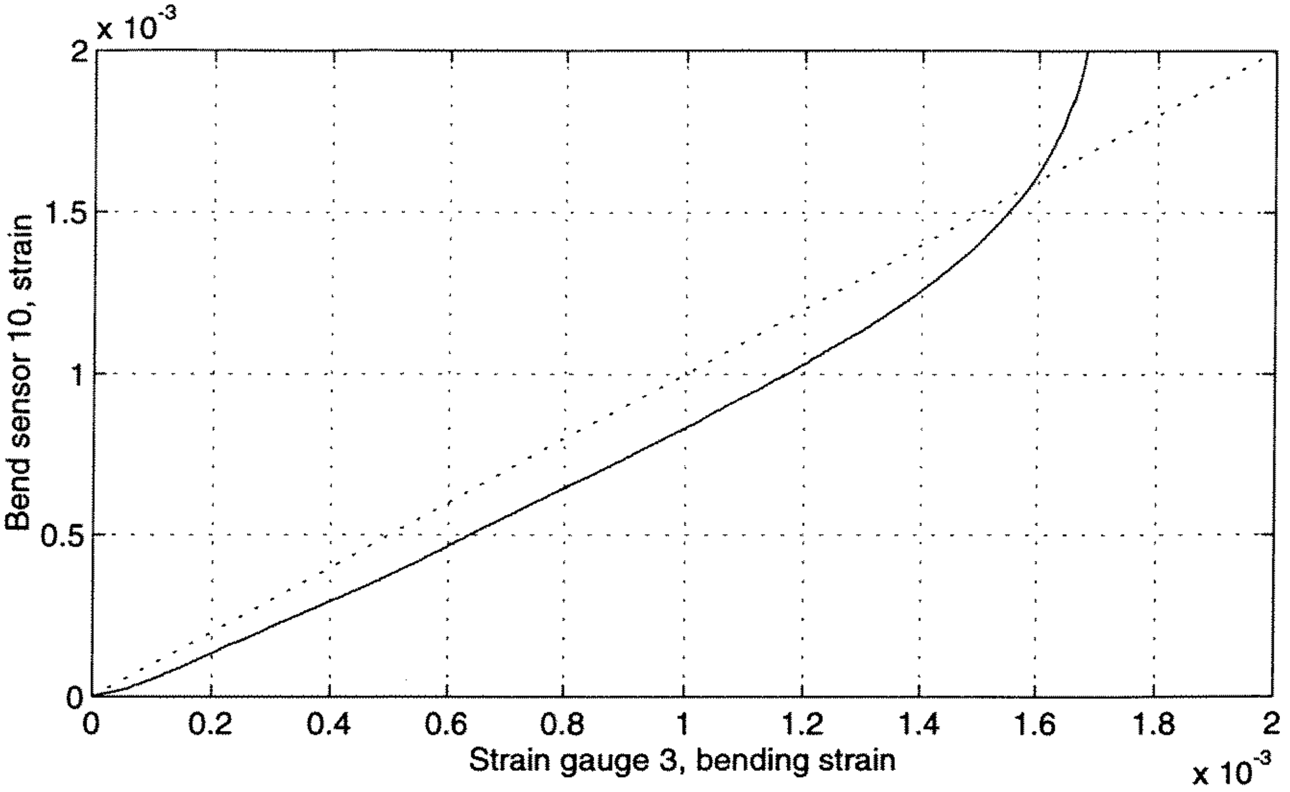
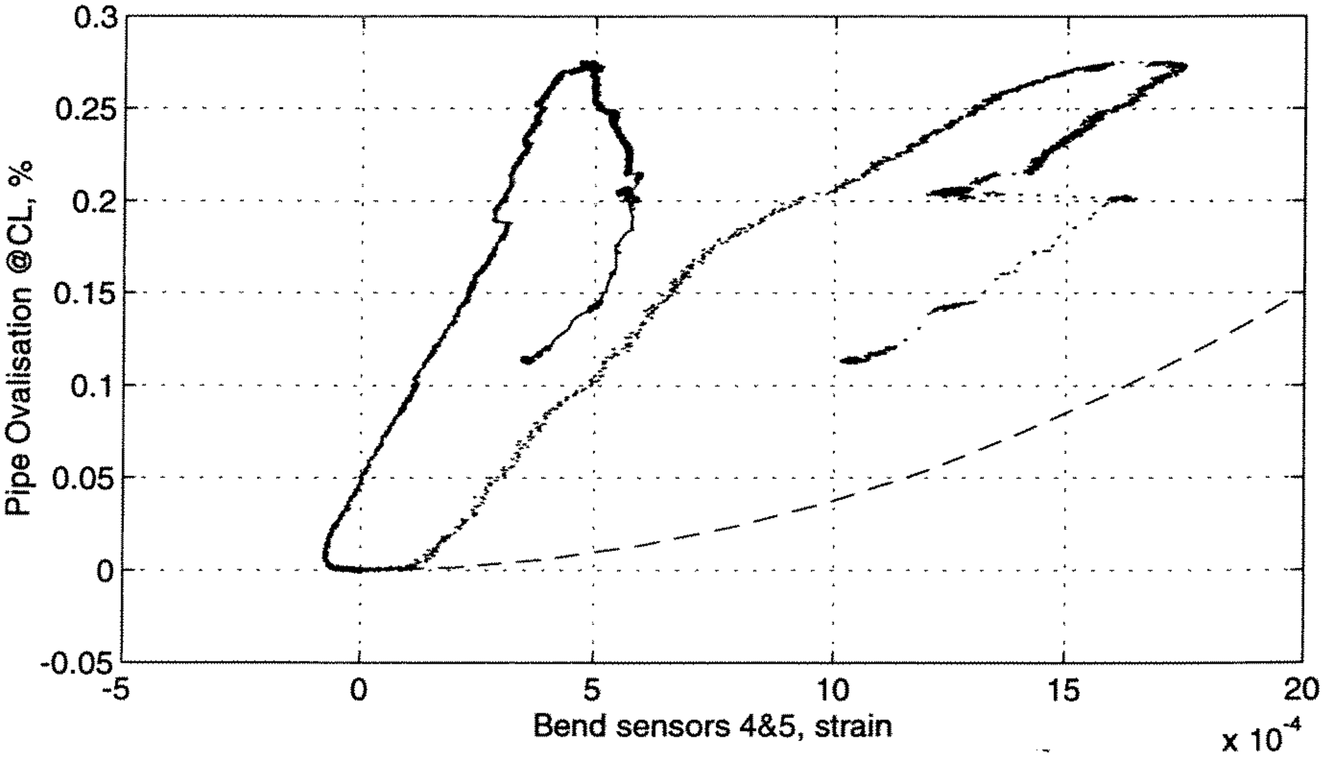
Bend Sensor Interpretation

Fig. No.
1





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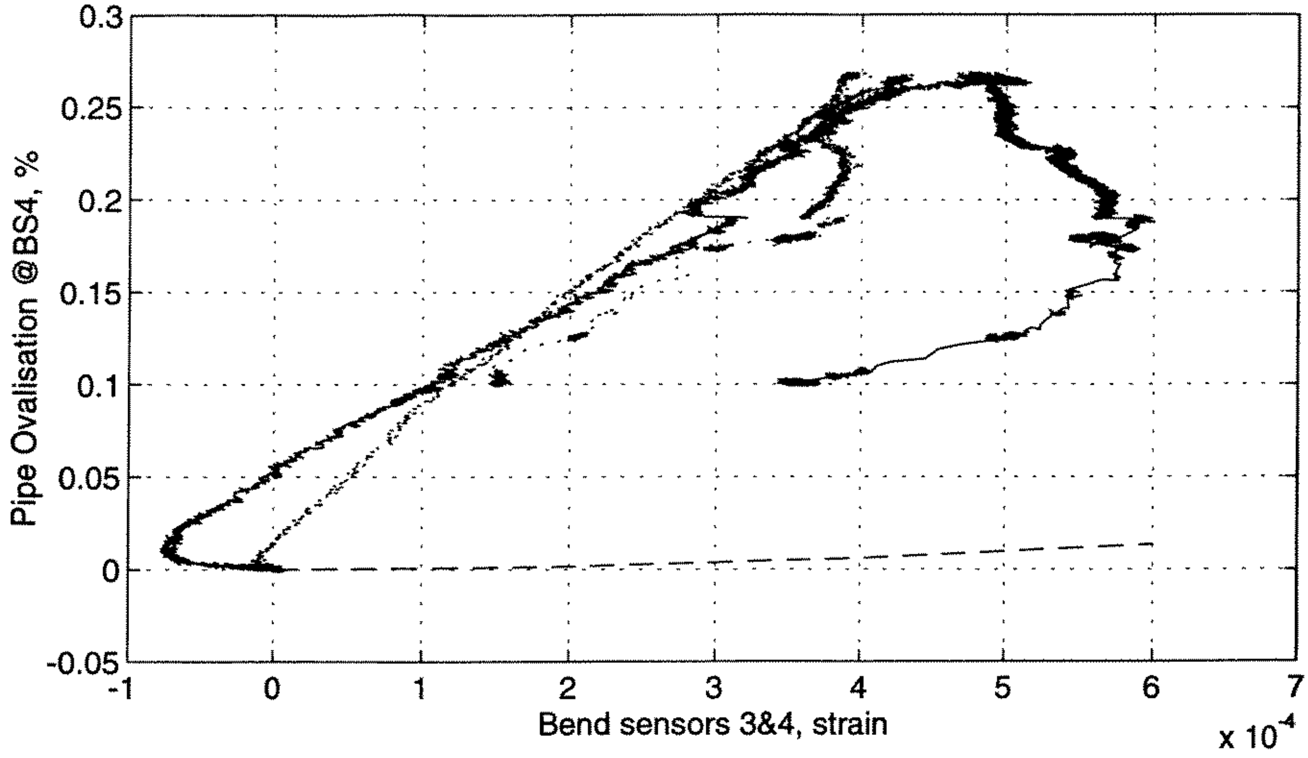
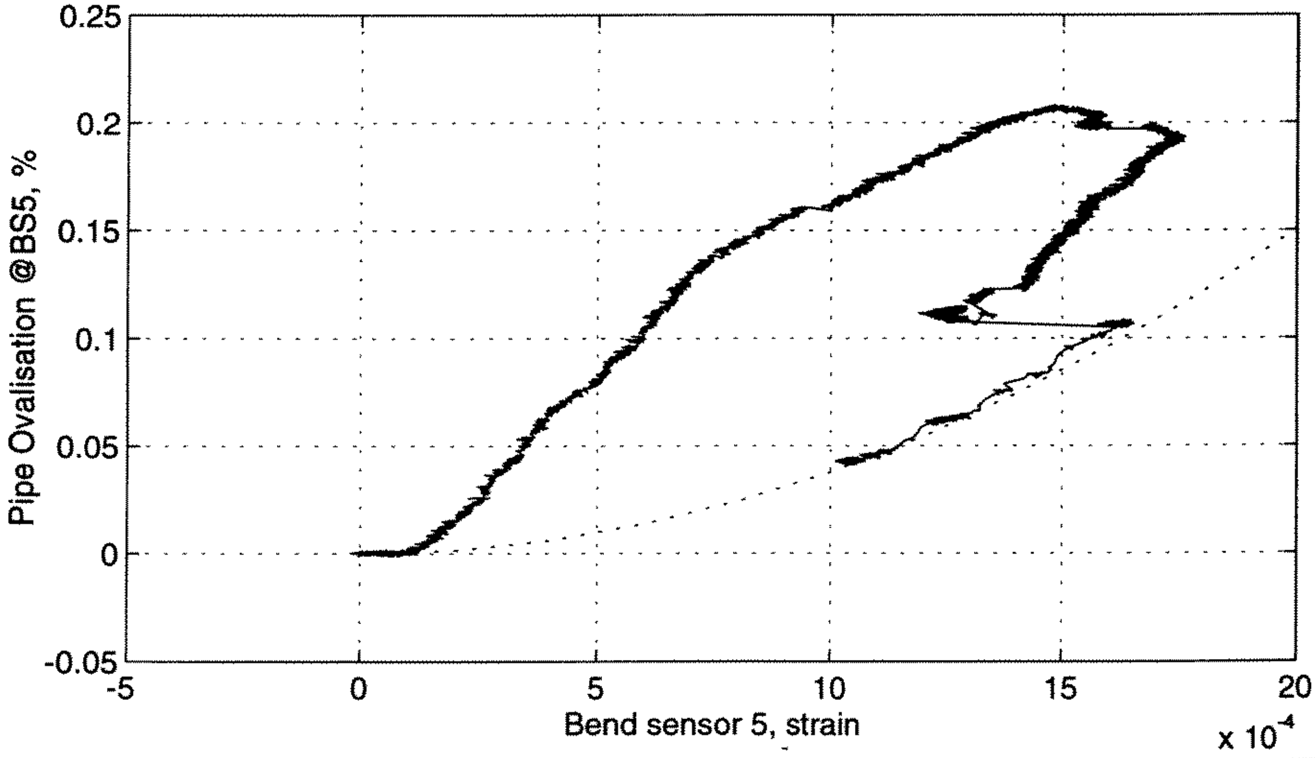
Typical Bend Sensor Strain Calibration
Pipe Centreline Ovalisation, GSC01

Fig. No.
2
3





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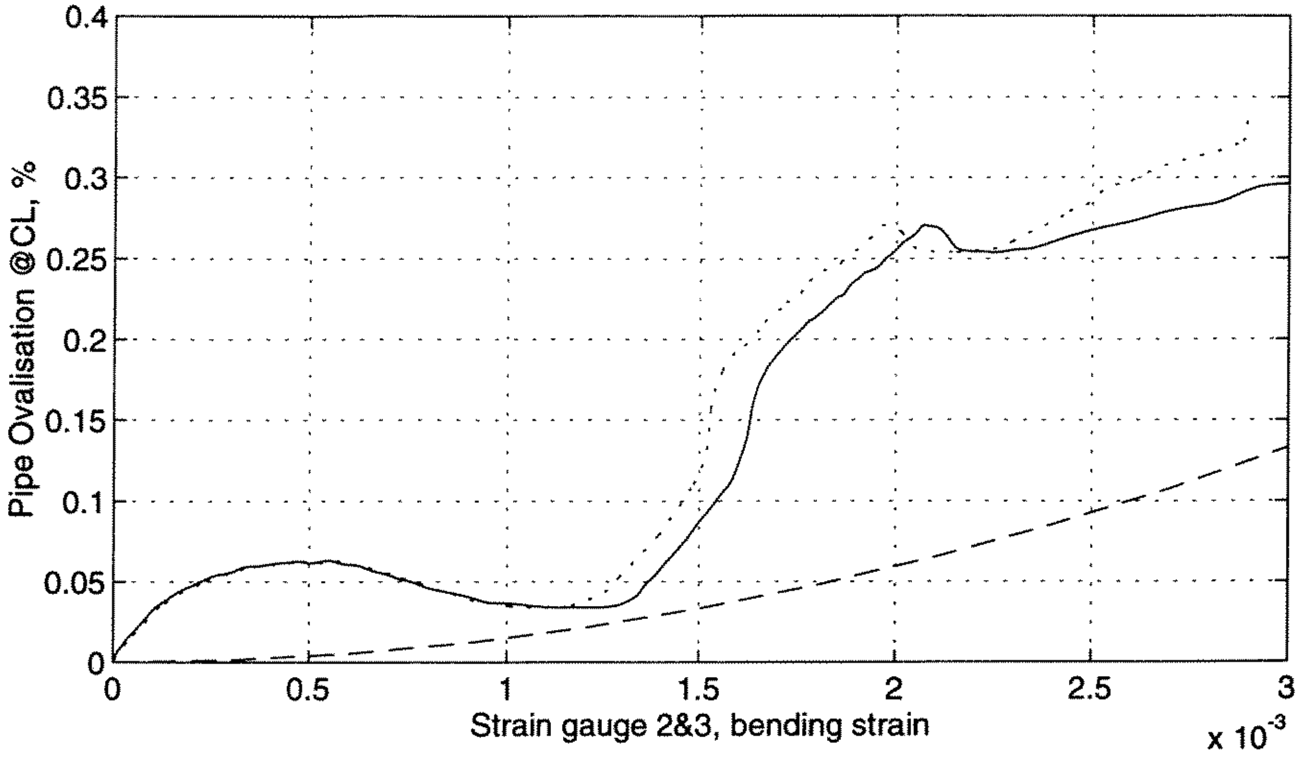
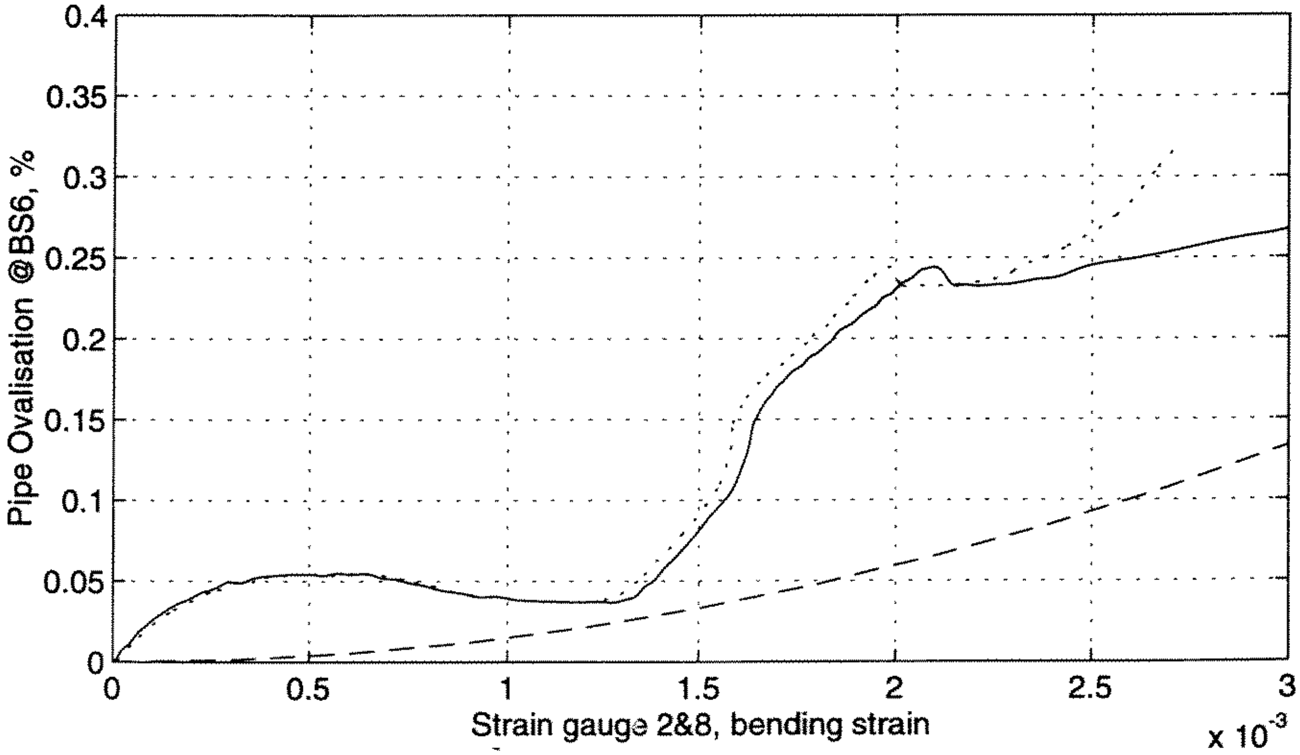
Pipe Ovalisation, Test GSC01
at Bend Sensor 4 and 5 Locations

Fig. No.
4
5





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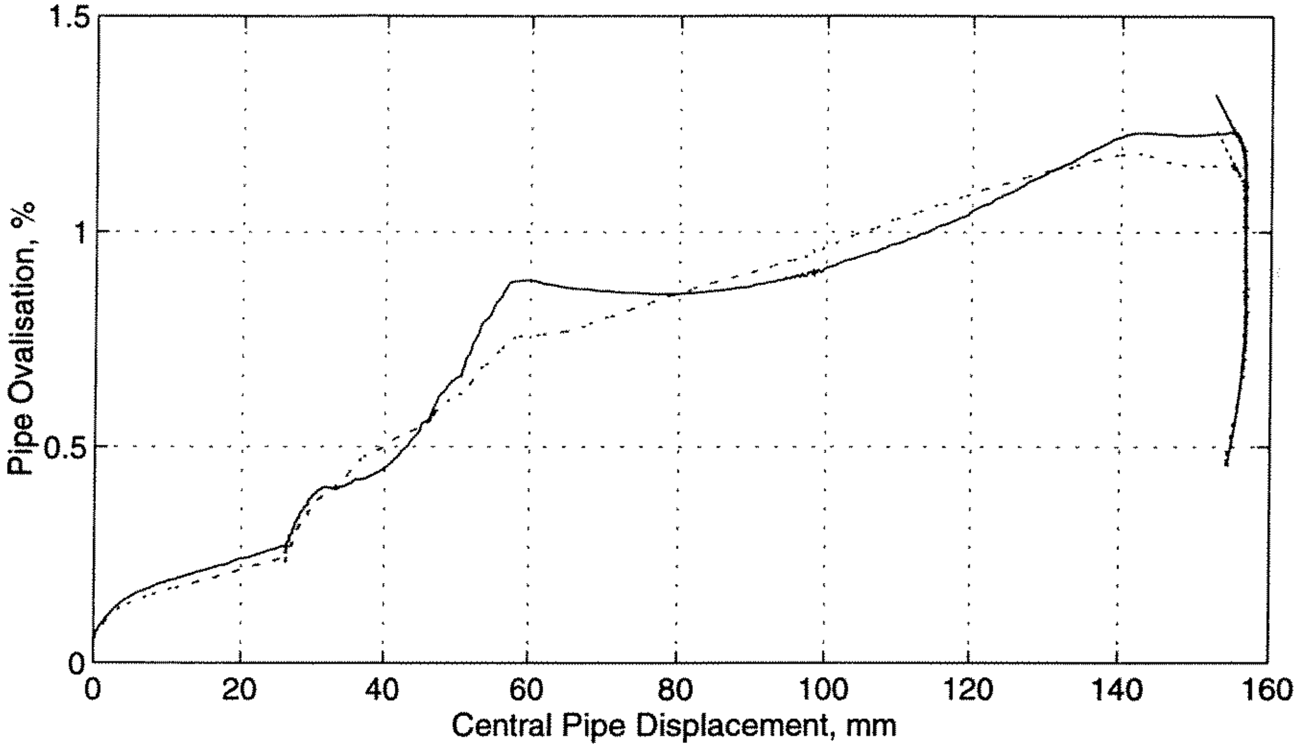
Pipe Ovalisation, Test GSC02, at Centreline & Bend Sensor 6 Location

Fig. No.
6
7



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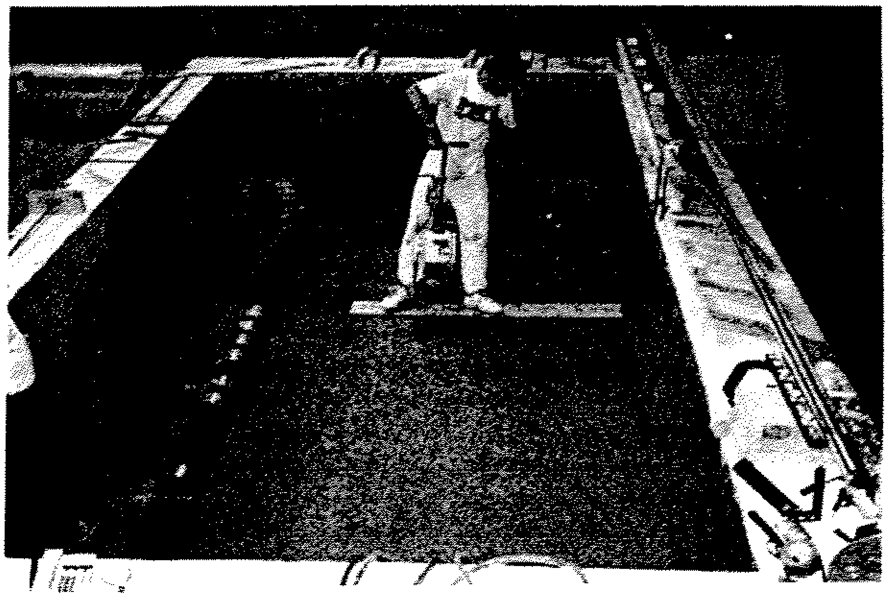
Pipe Ovalisation, Test GSC02
Development with Pipe Movement

Fig. No.
8



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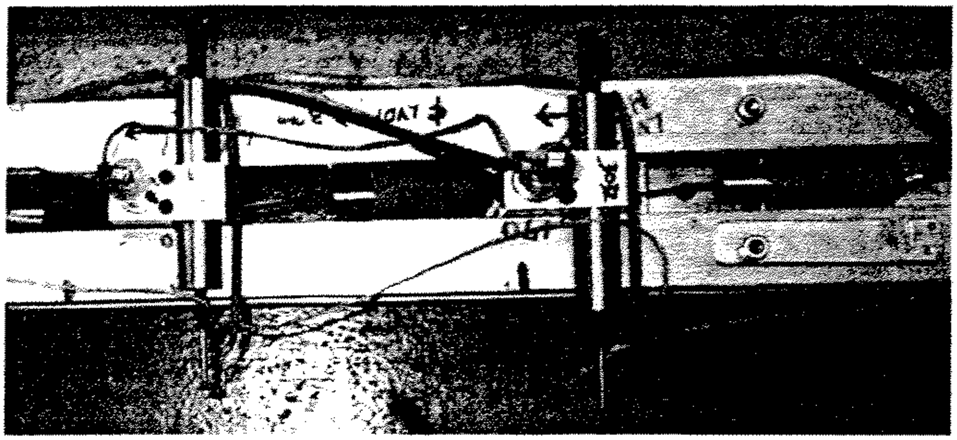
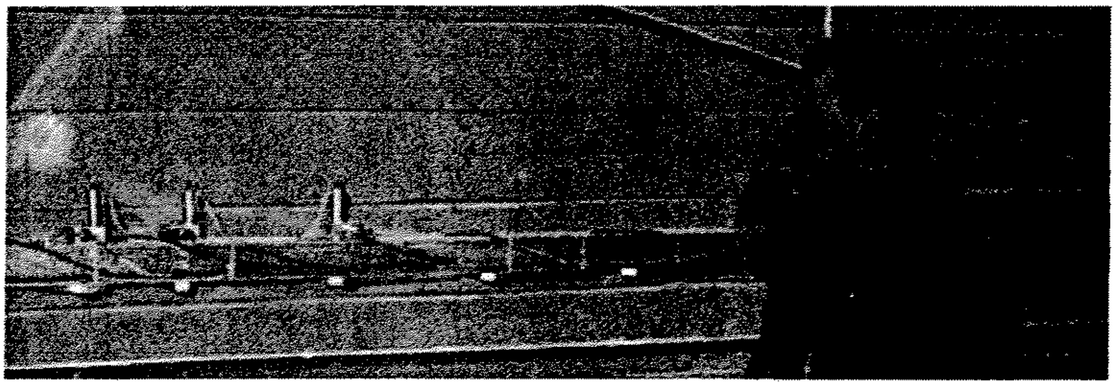
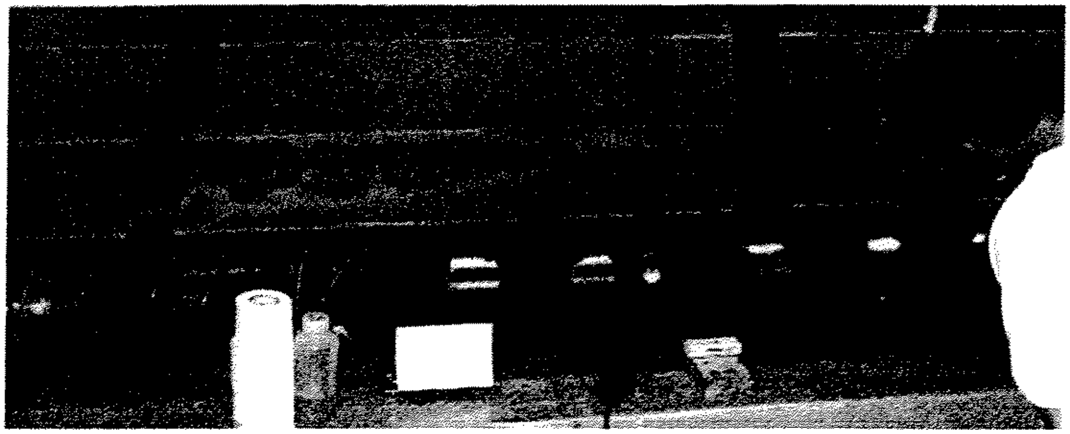
Test Preparation for GSC01
Typical Hinges in GSC01 and GSC02

Photo No.
A,B,C



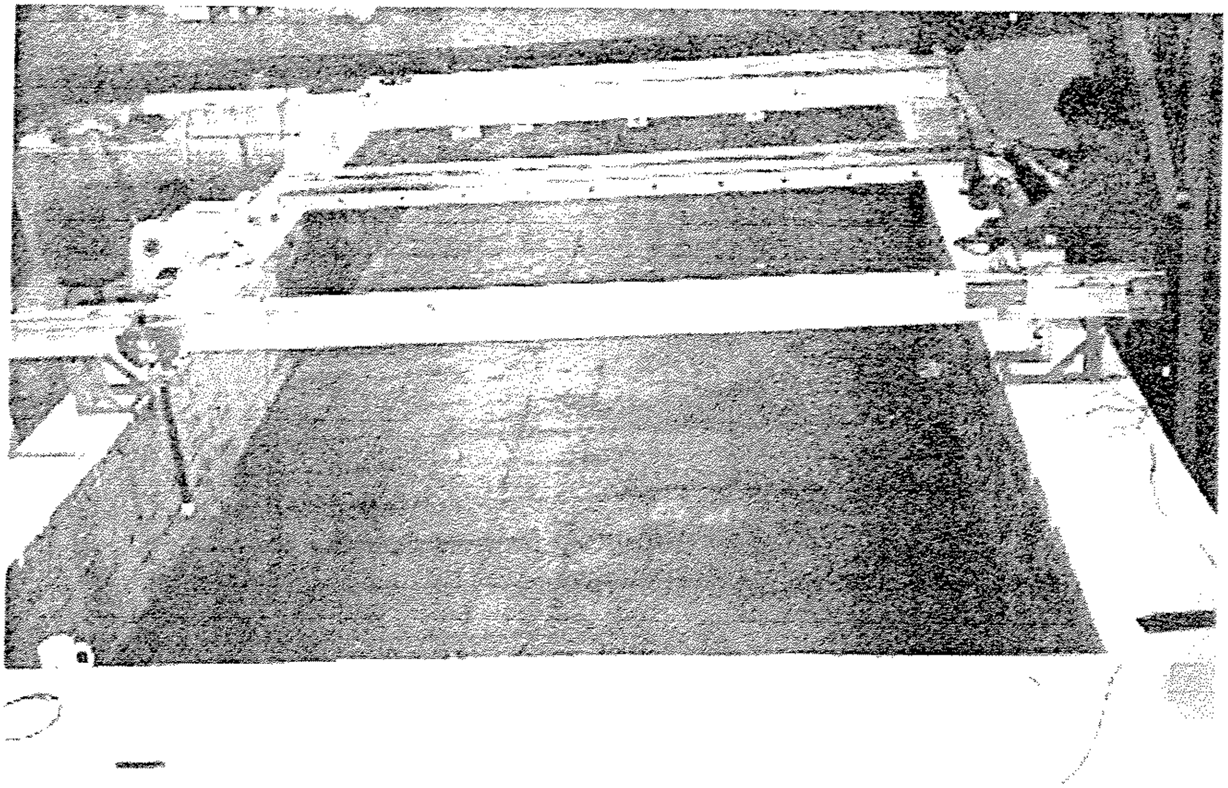
Note: Two channels removed after instrumentation installed

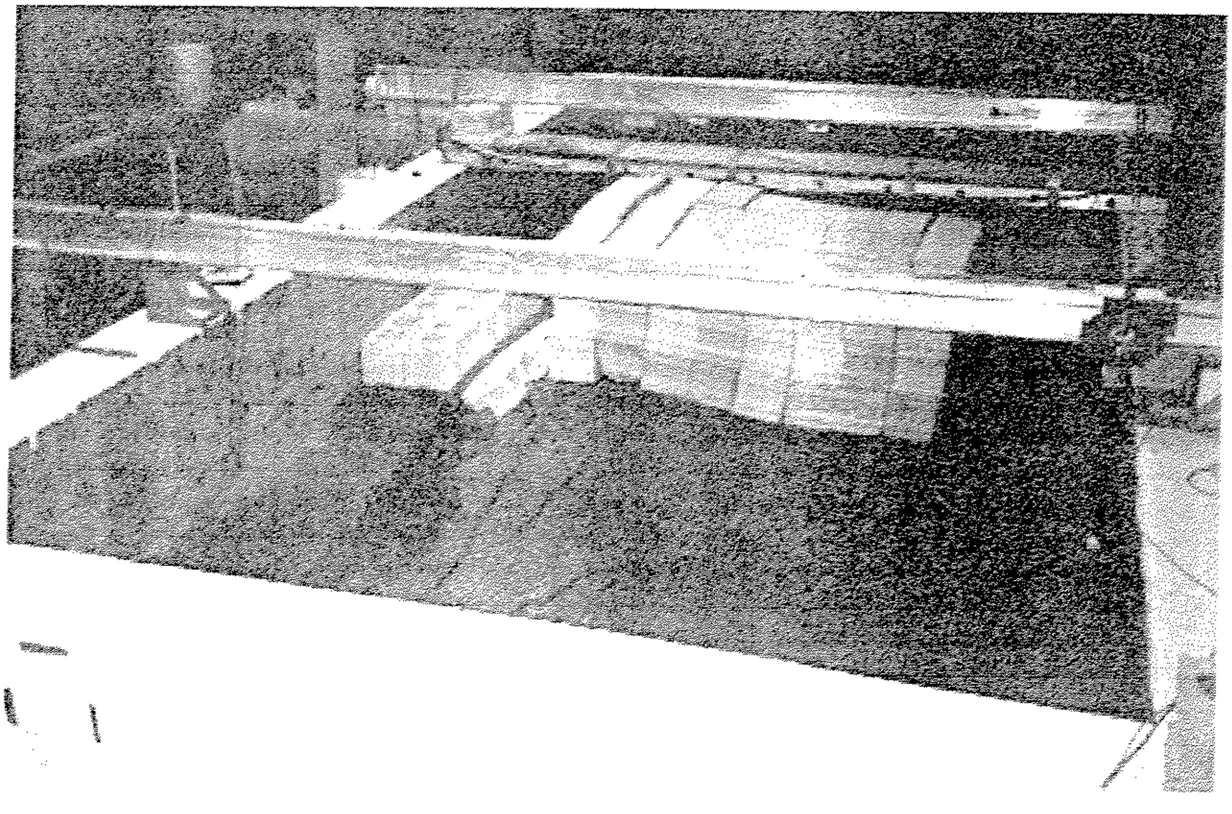




Note: Black grid and strain gauge locations

C-CORE	Ovalisation & Bend Sensor Layout,GSC02 Internal & External Pipe Instrumentation	**Photo No.** **D,E,F**





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Test Bed for GSC02
Pre & Post Test Images

Photo No.
G & H