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Correlating Field Performance of Long-Span 3-Sided Culvert Structures to Analysis Based on Soil-Structure Interaction Models

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CORRELATING FIELD PERFORMANCE OF LONG-SPAN 3-SIDED CULVERT STRUCTURES TO ANALYSIS BASED ON SOIL-STRUCTURE INTERACTION MODELS

In the past, the interaction between a buried structure, such as a culvert, and the surrounding soil was difficult to quantify. This required overly conservative design of buried structures as rigid frames using semi-empirical methods. With the development of finite element analysis and high performance computers, soil and structure can be modeled together, and soil-structure interaction becomes a viable design method enabling more accurate, more efficient designs. However, continued improvement and wide-spread acceptance of this method rely on additional correlation between the analyses and a structure's actual field performance.

In this study, a finite element analysis program specifically developed to analyze soil-structure interaction (CANDE) was used to analyze a long-span 3-sided precast concrete arch culvert. To verify the predicted reactions, a full-scale load test was conducted on the structure. Measured responses were compared with several finite element analyses using different soil models. For soil conditions at this site, which are typical of most culvert installations, the Selig model yielded the best correlation between the predicted behavior and the field performance. The correlation will allow more efficient and therefore more cost-effective designs for future structures.

Key words: soil-structure, 3-sided arch culvert, CANDE

ACKNOWLEDGMENTS

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INTRODUCTION

In the past, buried structures such as culverts were designed as rigid frames using semi-empirical methods. The surrounding soil was perceived as a load on the structure, rather than as contributing to the structure's strength.[1] This lead to very conservative, inefficient, and somewhat costly structures. More recently, finite element analysis has enabled soil and structure interaction to be considered in design. However, the accuracy of the analysis is dependent on the accuracy of the soil models that are used for the given site conditions. To determine the most appropriate soil model contained in CANDE (a finite-element-method program developed by FHWA) a full-scale load test was performed on a precast, 3-sided buried arch structure, and the field responses were compared to calculated values. Determination of the most appropriate soil model allows the design of more efficient and, therefore, more cost-effective structures.

PROFILE OF THE TEST STRUCTURE

The test bridge was designed by CON/SPAN Bridge Systems and the Montgomery County, Ohio, Engineer's Office staff for an AASHTO MS 22.5 (HS25-44) Truck Loading. A schematic diagram of the unit geometry is shown in Figure 1. In Figure 2, the relevant shop drawing showing the reinforcing is exhibited. To accommodate the 12.80-meter-wide roadway, the bridge was composed of seven precast concrete 11-meter-span 3-sided arch modular units. Each unit was 1.83 m wide with a 2.74 m rise. Essroc Materials, Inc. precast the units in their plant in Delaware, Ohio using mats of welded wire fabric to reinforce the inside and outside faces.

DESCRIPTION OF THE LOAD TEST

Test Preparations

The center unit of the seven-segment structure was selected for full-scale testing purposes. A schematic view of this unit with the instrumentation is exhibited in Figure 3. It should be noted that, for clarity, the view of the Dywidag (tie) rods and jacking beam in the reference figure is rotated 90 degrees from the actual installation.

A total of four soil pressure cells (Geokon model 4800E/C) were initially calibrated in the laboratory according to manufacturer's recommendations, then attached to the culvert through a set of bolts in over-sized holes mounted on backer plates. Backfill material meeting Ohio Department of Transportation (ODOT) Standard Specifications Section 304 was compacted in lifts per normal procedures up to the layer just below a pressure cell.[2] Prior to compaction of the layers containing the cells, an area of approximately 7.5 cm by 7.5 cm around the cells was replaced with loosely tamped sand to prevent damage to the assemblages. The remainder of fill placement and compaction proceeded per normal procedures.

Following the backfilling process, two high-strength tie rods extending through the structure were embedded and grouted into the rock below the bridge (Figure 3). These rods were coupled to a jacking system that contained a yoke, a jacking beam and a 890 kN hydraulic jack. The hydraulic jack reacted between the yoke (connected to the tie rods) and the jacking beam that distributed the load to two 1.22 m long steel tubes. The tubes were supported at each end on top of the precast unit. This resulted in a loading pattern of approximately 1.22 m by 1.22 m. Note that although the structure was designed for a moving live load, for the purposes of the test a single load case was considered. The 1.22m x 1.22m test loading pattern represented a tandem axle in the center of the structure.

A deflection test frame with 16 dial indicators at seven locations, as shown in Figure 3, was attached to the underside of the culvert prior to load application. Additional dial indicators were installed on the adjacent units to provide independent reference for the deflection measurements. Because the units were not connected, no load transfer to or deflection of these adjacent units was anticipated or observed.

Load Test

After the dial indicators were zeroed, the first load increment was applied up to 44.5 kN. Once the load stabilized (3 to 4 minutes), steady-state measurements from the dial indicators and the soil pressure cells were recorded. The load was then incremented by 44.5kN, and deflections and soil-pressure-cell readings were recorded. This procedure was repeated until the maximum jack capacity of 890 kN was reached. Cracking was monitored visually throughout the test. After the final loading of 890 kN, the load was released and the test unit was removed.

Post-Test Observations

The structure rebounded to 6.4 mm permanent deflection at the centerline when the simulated live load was removed. Crack widths at the center closed to widths prior to live load application (see Table 1). Also, inside surface cracks had closed such that they could not be seen on the edge of the unit. Examination of the test section after it was removed indicated that no cracking had occurred on the outside surface of the legs or the slab. The unit exhibited no visual signs of structural distress and could have remained in place.

FINITE ELEMENT ANALYSIS

The finite element program CANDE, developed by the FHWA, was employed for the soil-structure interaction study of the reference precast arch bridge. The finite element mesh with quadrilateral and triangular soil elements and thrust/bending structural elements is shown in Figure 4. Actual material properties were determined from the test unit, through core and steel testing, for use as input in the CANDE model. To simulate field conditions, the analysis was accomplished by modeling the structure and soil behavior during the different phases of installation, backfilling, and incremental vehicular live load applications.

Critical input parameters in CANDE are associated with the engineering soil properties. Several soil models have been developed and are built into CANDE, including: Isotropic Linear Elastic, Orthotropic Linear Elastic, Overburden Dependent, Duncan, and Selig models. The Duncan and Selig models are non-linear, and they have several built-in sets of parameters to represent a range of soil types.[3] An attempt was made to verify the structural response with respect to each of these soil models using the field-determined soil properties as input.

The subsurface exploration revealed bedrock at the foundation level, consisting of the Richmond Formation with alternating layers of shale and hard limestone. Selig's built-in parameters for special materials, in this case rock, were employed in the analysis for the foundation bed. The backfill material used was a well-graded granular material, per ODOT Standard Specifications Section 304, which had been compacted to 95% of the Standard Proctor density (19.93 kN/m^3). Measured and calculated values for the internal friction angle, ϕ, and the failure ratio, R_f, (R_f = failure deviator stress/ultimate deviator stress) were 42° and 0.7, respectively. This corresponded to the built-in Selig parameters for stiff materials.[4] The values for the built-in Selig model variables and the values that were changed are shown in Table 2 for both materials.

RESULTS AND DISCUSSION

In the past, buried structures such as culverts were designed using the surrounding soil only as a dead load on the structure, rather than as a component of the structural strength. The current case of the 3-sided arch, however, illustrates that as the weights of the soil prism above the crown and the live load press the top of the structure downward, the side walls tend to move outward. Due to restraint offered by the surrounding backfill, a thrust is developed in the top slab of the unit, creating an arch action which increases the load-carrying capacity of the culvert-soil system as compared with a free-standing (without any backfill) structure. Thus, the behavior of the culvert is dependent on its interaction with the surrounding soil and can be simulated closely using a finite element model.

The validation of assumptions regarding the engineering material properties and soil-structure interaction mechanisms is essential for the acceptance of finite element analysis and design. Therefore, the primary purpose of this study was to compare and verify the results predicted by a CANDE computer analysis to the results obtained from the load test.

The structural response of the test unit was verified with respect to five soil models contained in CANDE (Isotropic Linear Elastic, Orthotropic Linear Elastic, Overburden Dependent, Duncan, and Selig models), using the field-determined soil properties as input. Since soil is generally neither a linear-elastic nor a constant-stiffness material, the two Linear Elastic models gave expectedly poor correlation with the field results. The Overburden Dependent soil model varies soil stiffness with overburden pressure, but only for one-dimensional compression of the soil. In zones where two-dimensional compression is prevalent, such as near culverts or walls , this model is not accurate.[5] Thus, it gave poor correlation as well. As anticipated, better correlation was obtained with the last two models. The Duncan model uses variable Young's and bulk moduli. Both of these moduli increase with confining stress, and Young's modulus decreases with increasing shear stress.[6] The Selig model is an extension of the Duncan model, but it uses an alternate formulation for the bulk modulus which is hyperbolic.[6,7,8] Because both the Duncan and Selig models have hyperbolic formulations for Young's modulus, they approximate the soil stress-strain curve more closely and thus correlate the calculated response with the field measurements very well. The Selig model gave the best results, probably due to its different bulk modulus formulation.

The centerline displacement recorded during the load test and the corresponding load increments are plotted in Figure 5. Also shown in this figure is the variation of the load-displacement predicted by the CANDE analysis. It is evident that both CANDE and the field data follow essentially the same trend up to 267 kN load, beyond which there is a deviation between the two. Beyond 267 kN, the CANDE model conservatively predicts higher centerline deflections than were actually seen during the load test.

The predicted and field-measured deflections at the full design service load (per AASHTO) of 116 kN are both approximately 1.6 mm. This is only 12% of the L/800 allowed per AASHTO Specifications. The deflection corresponding to the minimum required design ultimate strength (per AASHTO) of 254 kN is about 4.0 mm as measured in the field, and 4.5 mm based on CANDE, a difference of only 12%. The maximum deflection at the center line of the culvert is less than 38 mm at 890 kN applied load as measured. This compared with 44.5 mm calculated by CANDE, a deviation of 17%. These results suggest that very good correlation exists between CANDE predictions and actual field performance under design conditions. The accuracy is decreased beyond design loads; but, overall, reasonably good correlation exists between the CANDE analysis and that of field data regarding the center line displacement. A similarly good correlation between load test measurements and the CANDE analysis was observed at the other dial gauge locations. As expected, the displacement values at the base of the legs were negligible for all the load increments, due to the placement of the legs in a grouted keyway in the footing. Therefore, a pin support condition at the culvert foundation is appropriate in the CANDE model.

The data in Figure 6, which illustrate the load increments versus the normal soil pressure distribution on the east and west sides of the culvert for the top pressure cells, prove to be in excellent agreement with the CANDE analysis. Furthermore, the increase in the magnitude of normal soil pressure at higher load increments indicates the important role that the surrounding soil plays. As the structure deflects further, it mobilizes the passive resistance of the backfill material.

The earth pressure distribution at varying load increments for the bottom soil pressure cells on the east side of the unit is shown in Figure 7. Also shown in this figure are the results from analysis by the CANDE computer model. It is observed that, at greater than AASHTO design loads (MS22.5), the pressure distribution calculated by the CANDE program deviates from the field-measured values. For these conditions, CANDE predicts higher normal pressures at the bottom of the leg than were measured in the field. The cause for such discrepancy is not apparent and further investigation is required.

CONCLUSION

The test unit of the installed bridge performed exceptionally well under extreme loading conditions. It carried a load greater than seven and one-half times AASHTO's heaviest design service load (MS22.5). Although the intent of this study was to load the structure to failure, or the point when the steel reinforcing first yielded, this never occurred due to limitation of the hydraulic jack capacity.

Live-load deflections and earth pressures measured from the test unit were compared with finite element computer analyses in order to verify the soil models contained in CANDE. For the type of backfill material used at this site, i.e., a well-graded granular soil that is typical of most culvert installations, the study revealed that the Selig soil model presented the best correlation between the predictions of CANDE and the culvert's field performance. This correlation also validates the use of soil-structure interaction as an appropriate design method, which will allow more efficient and more cost-effective designs for future structures.

REFERENCES

1. *Standard Specifications for Highway Bridges.* American Association of State Highway and Transportation Officials, Washington, D.C., 1992.
2. *CON/SPAN Specifications for Manufacture and Installation of CON/SPAN Bridges.* CON/SPAN Bridge Systems, Dayton, Ohio, 1992.
3. Musser, S.C., *CANDE 89 - Culvert Analysis and Design Program, User Manual.* Report No. FHWA-RD-89-169. FHWA, U.S. Department of Transportation, 1989.
4. Selig, E.T., Soil Parameters for Design of Buried Pipelines. ASCE Conference on Pipeline Infrastructure, June 1988
5. Katona, M.G., Smith, J.M., Odello, R.S., and Allgood, J.R. *CANDE: A Modern Approach for the Structural Design & Analysis of Buried Culverts.* Report No. FHWA-RD-77-5, FHWA, U.S. Department of Transportation, 1976.
6. Duncan, J.M., Byrne, P., Wong, K.S., and Mabry, P. *Strength, Stress-strain and Bulk Modulus Parameters for Finite Element Analysis of Stresses and Movements in Soil Masses.* University of California College of Engineering, Berkeley. Report No. UCB/GT/80-01, 1980.
7. Lin, R-S.D., *Direct Determination of Bulk Modulus of Partially Saturated Soils.* University of Massachusetts, Amherst. Report No. ACP87-341P for M.S. Degree, 1987.
8. Yang, G-R., *Hyperbolic Young's Modulus Parameters for Compacted Soils.* University of Massachusetts, Amherst. Project Report ACP87-Pe for M.S. Degree. 1987.

Table 1: OBSERVED CRACK WIDTHS (in mm)

LOAD LEVEL	LOCATION		
	20 cm left	Centerline	20 cm right
Initial *(prior to live load)*	0.05	0.05	0.05
44.5 kN	0.05	0.05	0.05
90.0 kN	0.05	0.05	0.05
133.4 kN	0.05	0.05	0.05
177.9 kN	0.13	0.13	0.13
222.4 kN	0.13	0.13	0.13
266.9 kN	0.13	0.13	0.13
311.4 kN	0.13	0.13	0.13
355.9 kN	0.13	0.13	0.13
400.3 kN	0.13	0.13	0.13
444.8 kN	0.13	0.13	0.13
489.3 kN	0.13	0.13	0.13
533.8 kN	0.13	0.13	0.13
578.3 kN	0.13	0.19	0.13
622.8 kN	0.19	0.19	0.19
667.2 kN	0.19	0.19	0.19
711.7 kN	0.19	0.25	0.25
756.2 kN	0.19	0.25	0.25
800.7 kN	0.19	0.25	0.25
845.2 kN	0.19	0.25	0.25
889.6 kN	0.19	0.29	0.29
Unloaded	0.05	0.05	0.13

Table 2: SOIL PROPERTIES

BACKFILL SOIL (SELIG MODEL)

	UNIT WT (kN/m^3)	K	n	R_f	B_i/P_a	ε_u	C (kPa)	ϕ (deg)	$\Delta\phi$ (deg)	k_0
Value recommended	19.64	408	0	0.7	340	100000	689	50	0	1
Value changed		450								

BELOW FOUNDATION & EXTREME ENDS (SELIG MODEL)

	UNIT WT (kN/m^3)	K	n	R_f	B_i/P_a	ε_u	C (kPa)	ϕ (deg)	$\Delta\phi$ (deg)	k_0
Value recommended	22.77	6800	0	0.7	3800	100000	689	50	0	1
Value changed										

FIGURE 1

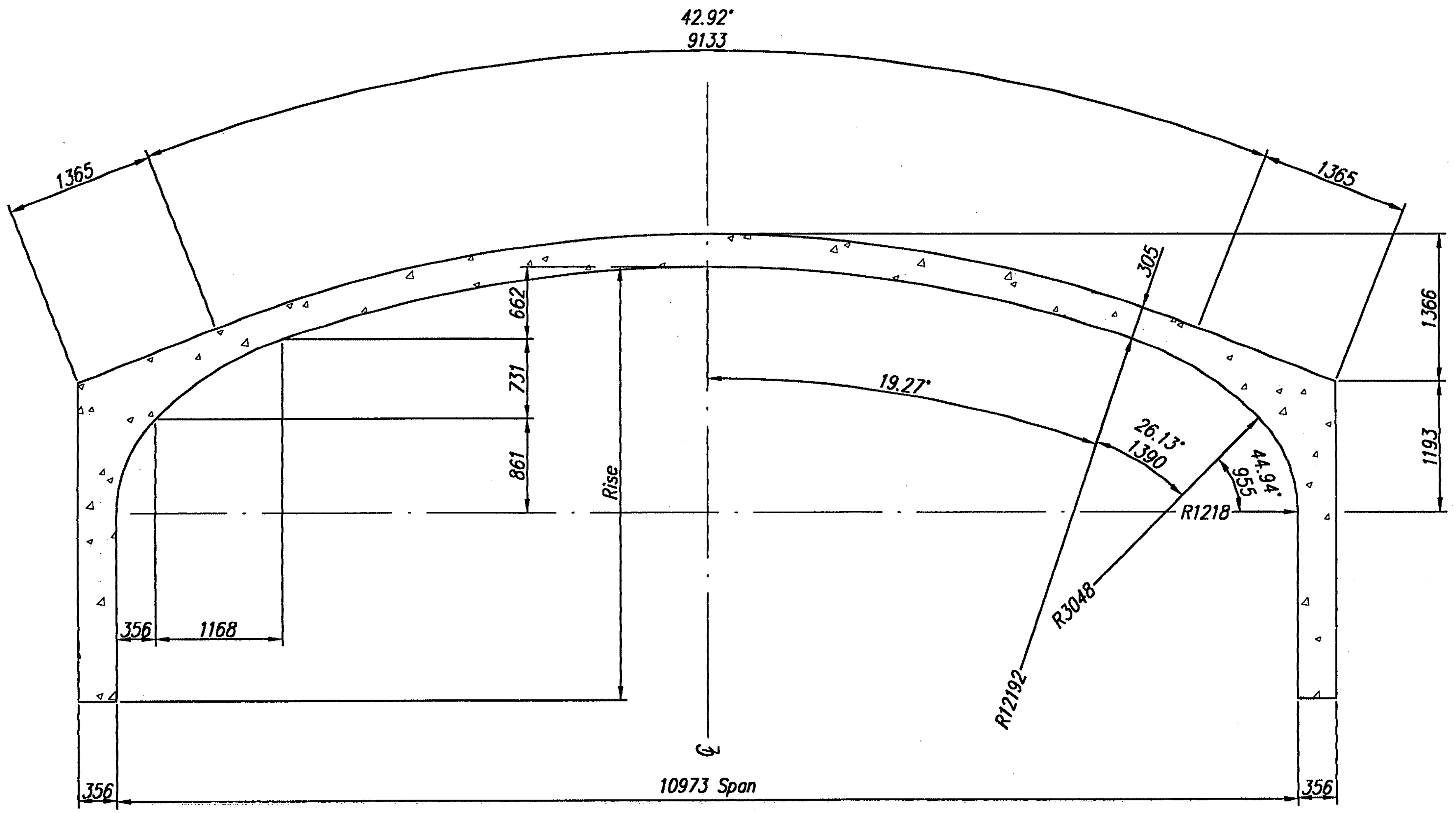
42.92°
9133
1365
1365
305
1366
1193
662
731
861
Rise
19.27°
26.13°
1390
44.94°
955
R1218
R3048
R12192
356
1168
℄
356
10973 Span
356

FIGURE 2

Con/Span®
Bridge Systems

1563 East Dorothy Lane
Dayton, Ohio 45429
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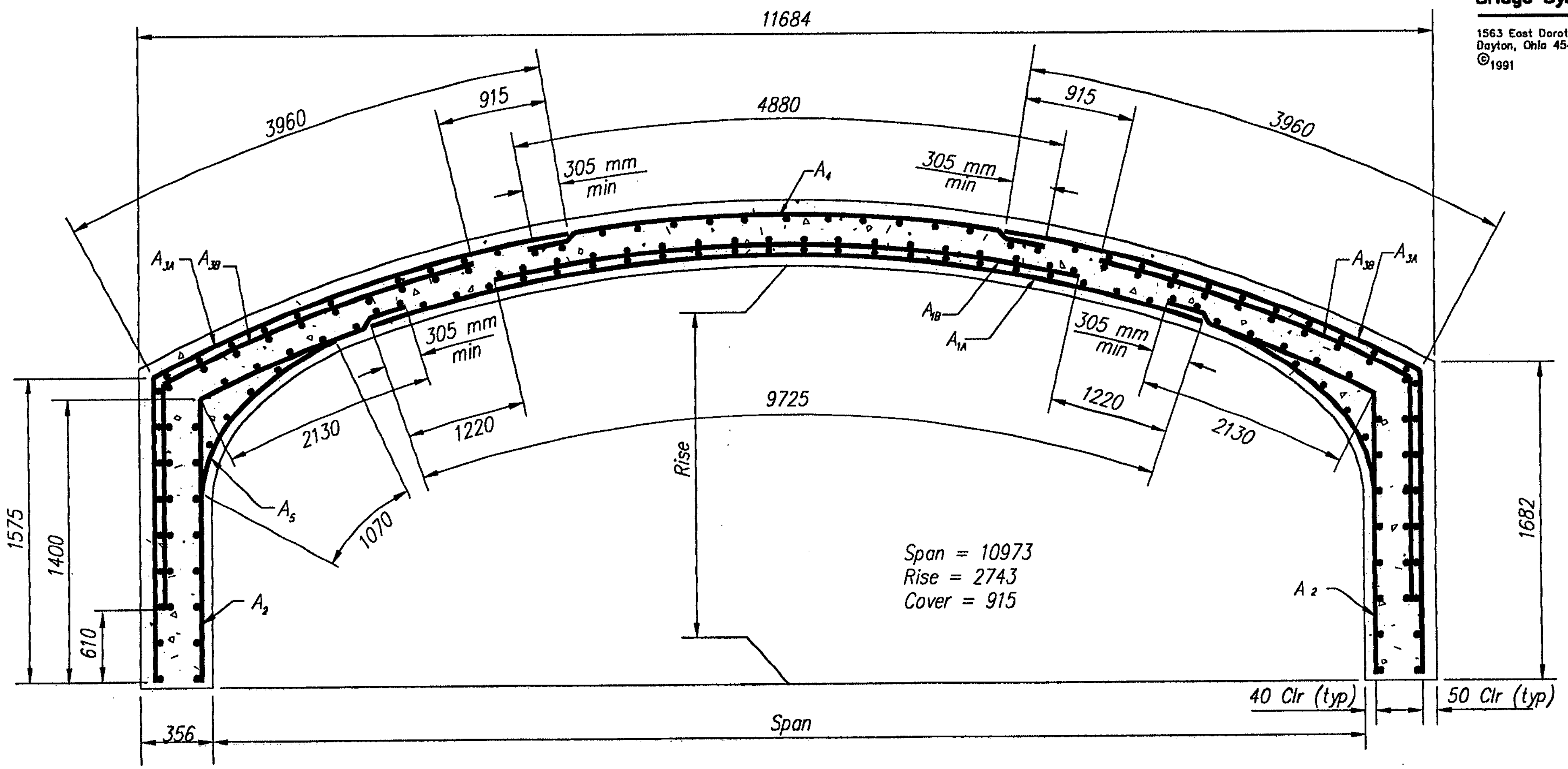


Span = 10973
Rise = 2743
Cover = 915

Sheet no.	Circumferential Area Req'd (cm²/m)	Longitudinal Area Req'd (cm²/m)	Mesh Size	Length (m)	Circumferential Area Supl'd (cm²/m)	Longitudinal Area Supl'd (cm²/m)
1	A1a = 15.2	2.8	50x200 W12	7.925	15.2	2.8
2	A1b = 12.7		50x200 W10	5.485	12.7	
3	A2 = 10.2	2.8	50x200 W8	3.530	10.2	2.8
4	A3a = 12.7	2.8	50x200 W10	5.535	12.7	2.8
5	A3b = 12.7		50x200 W10	4.010	12.7	
6	A4 = 10.2	2.8	50x200 W8	4.880	10.2	2.8
7	A5 = 10.2	2.8	50x200 W8	1.070	10.2	2.8

Design Loading: HS25-44

NOTES

1. Overlap lengths are measured from crosswire to crosswire.
2. Minimum 28-day concrete compressive strength shall be 41.4 MPa.
3. Dimensions shown are based upon form system "A".
4. Steel strength for WWF shall be 414 MPa.
5. Dimensions are in millimeters unless noted otherwise

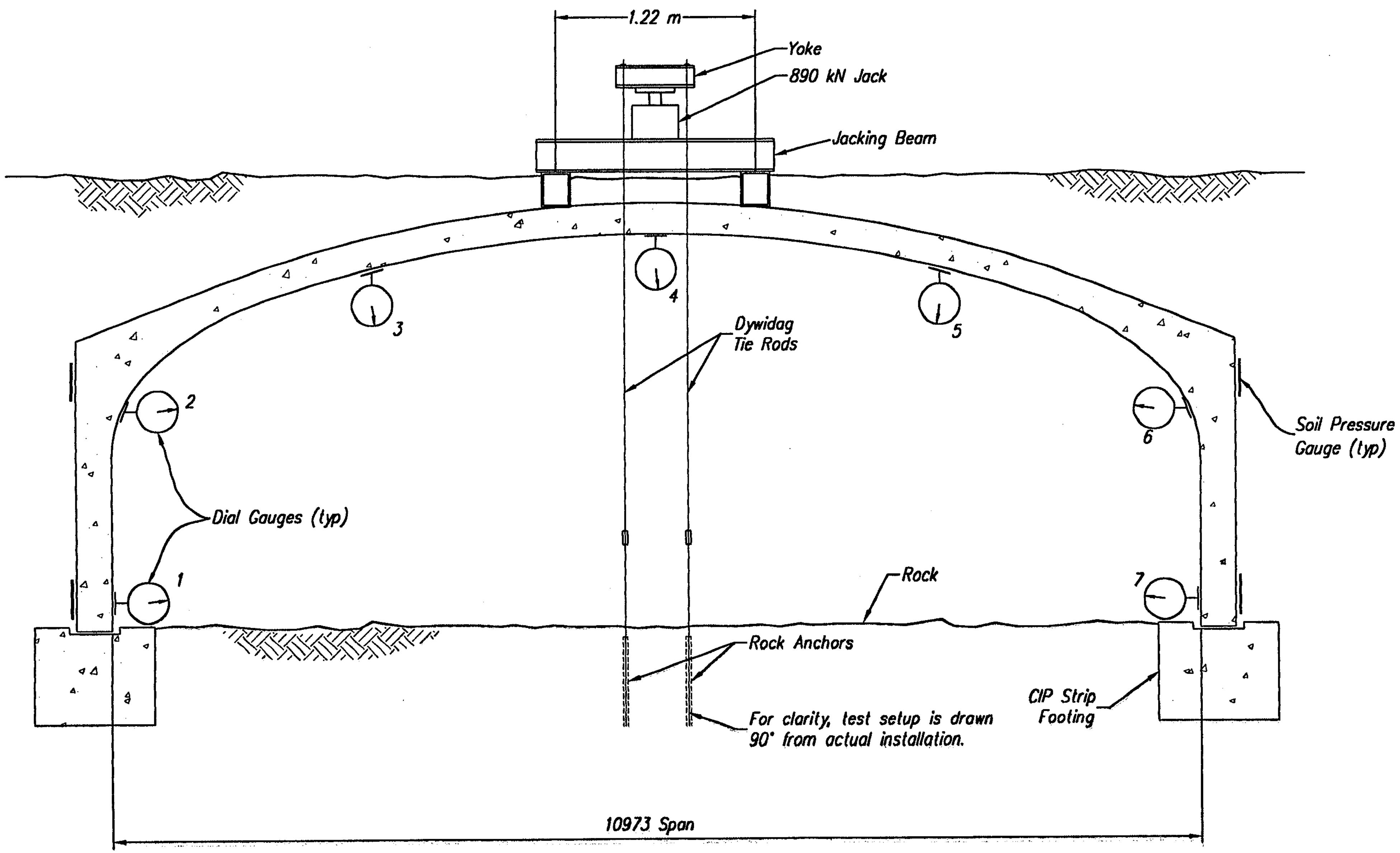
Producer: ESSROC
DELAWARE, OH

Project: # 2404
Gay Road Bridge
Montgomery County

Date:
Appr'd by:

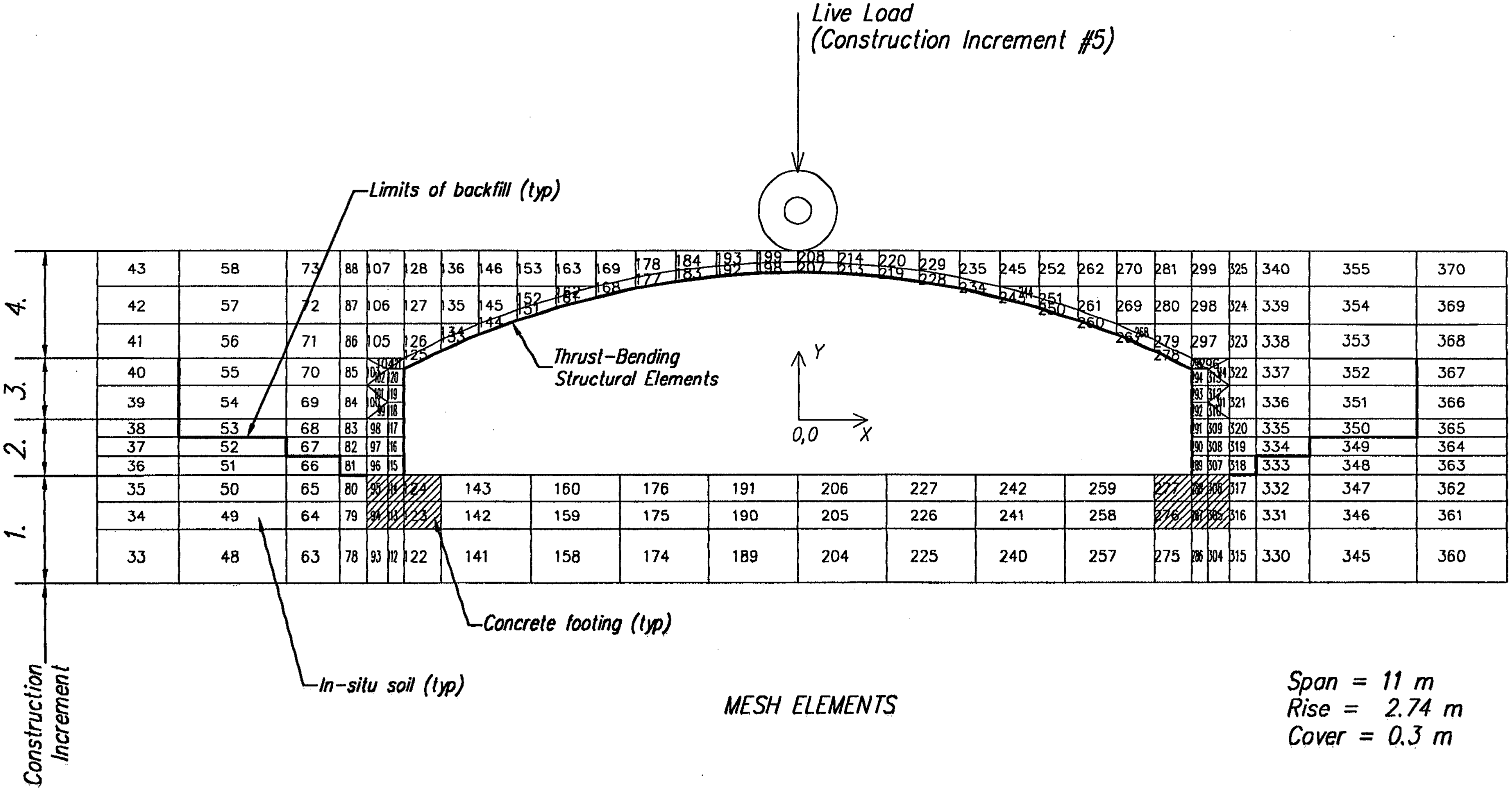
Con/Span is a patented system and the furnishing of this drawing does not constitute an express or implied license.

FIGURE 3



For clarity, test setup is drawn 90° from actual installation.

FIGURE 4



MESH ELEMENTS

Span = 11 m
Rise = 2.74 m
Cover = 0.3 m

FIGURE 5

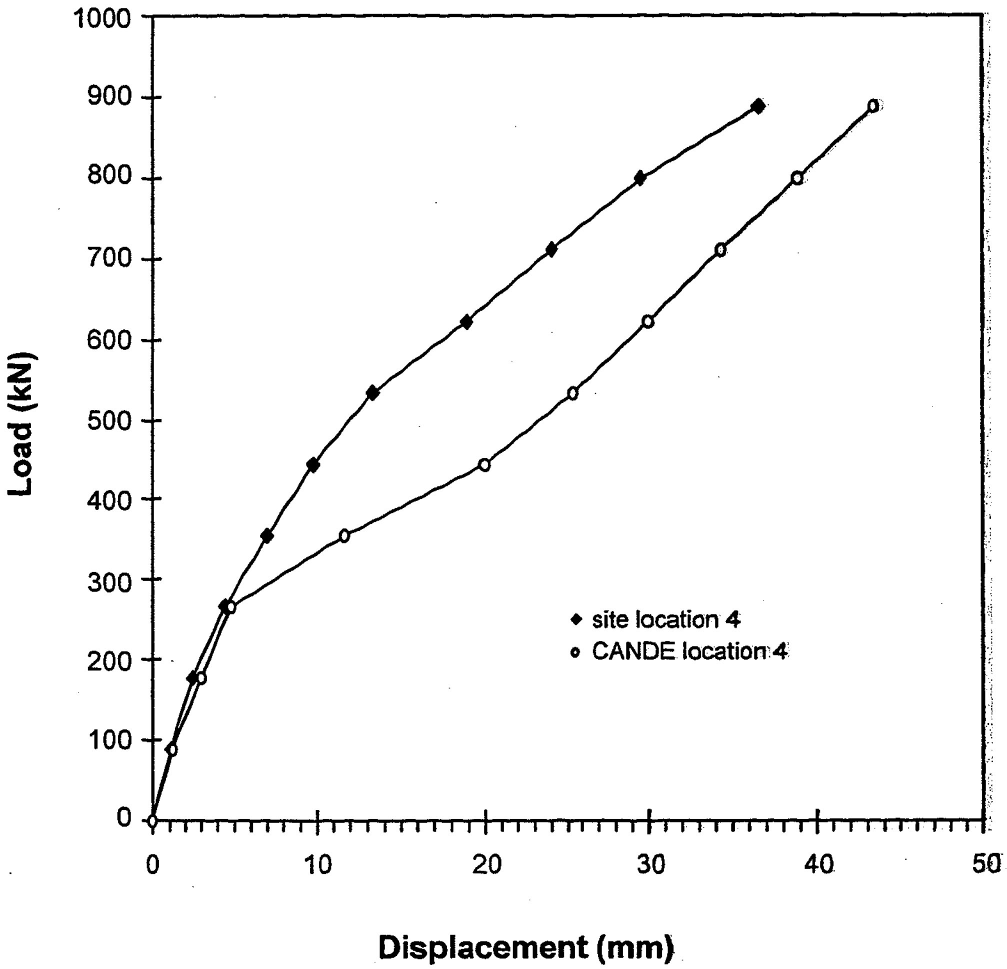

1000
900
800
700
600
500
400
300
200
100
0
Load (kN)
0
10
20
30
40
50
Displacement (mm)
◆ site location 4
○ CANDE location 4

FIGURE 6

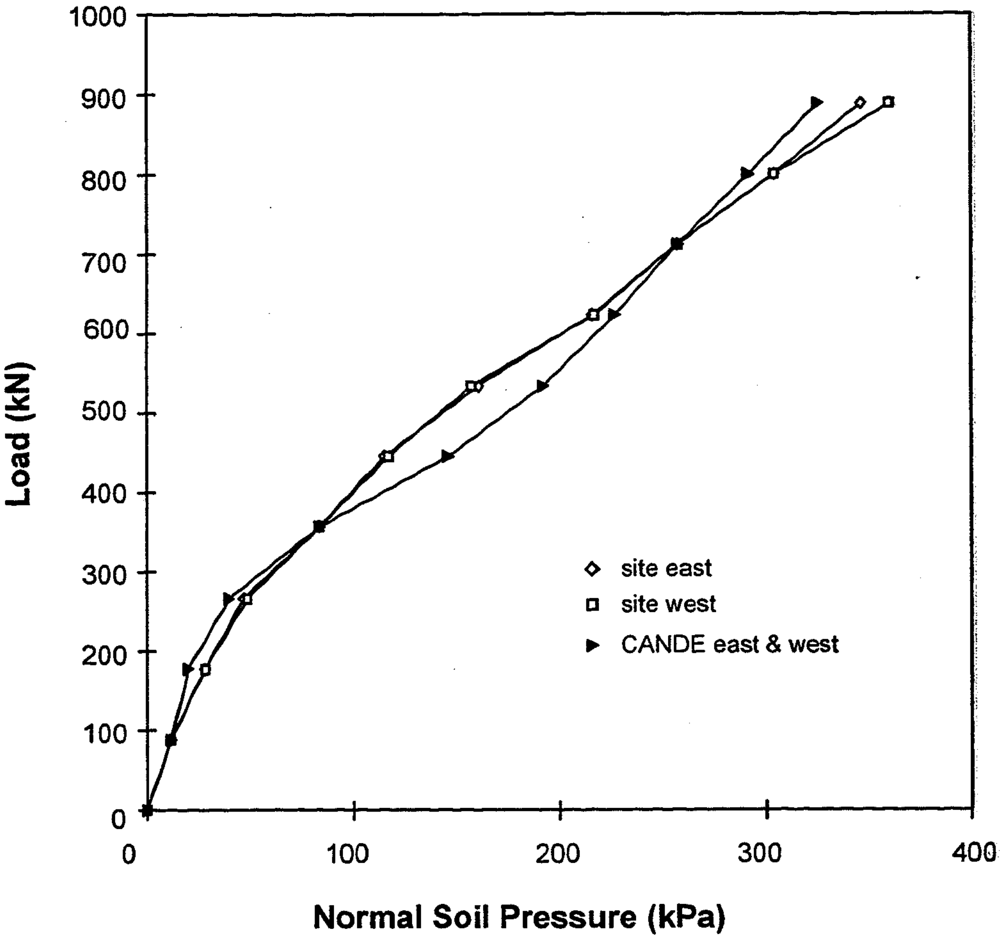
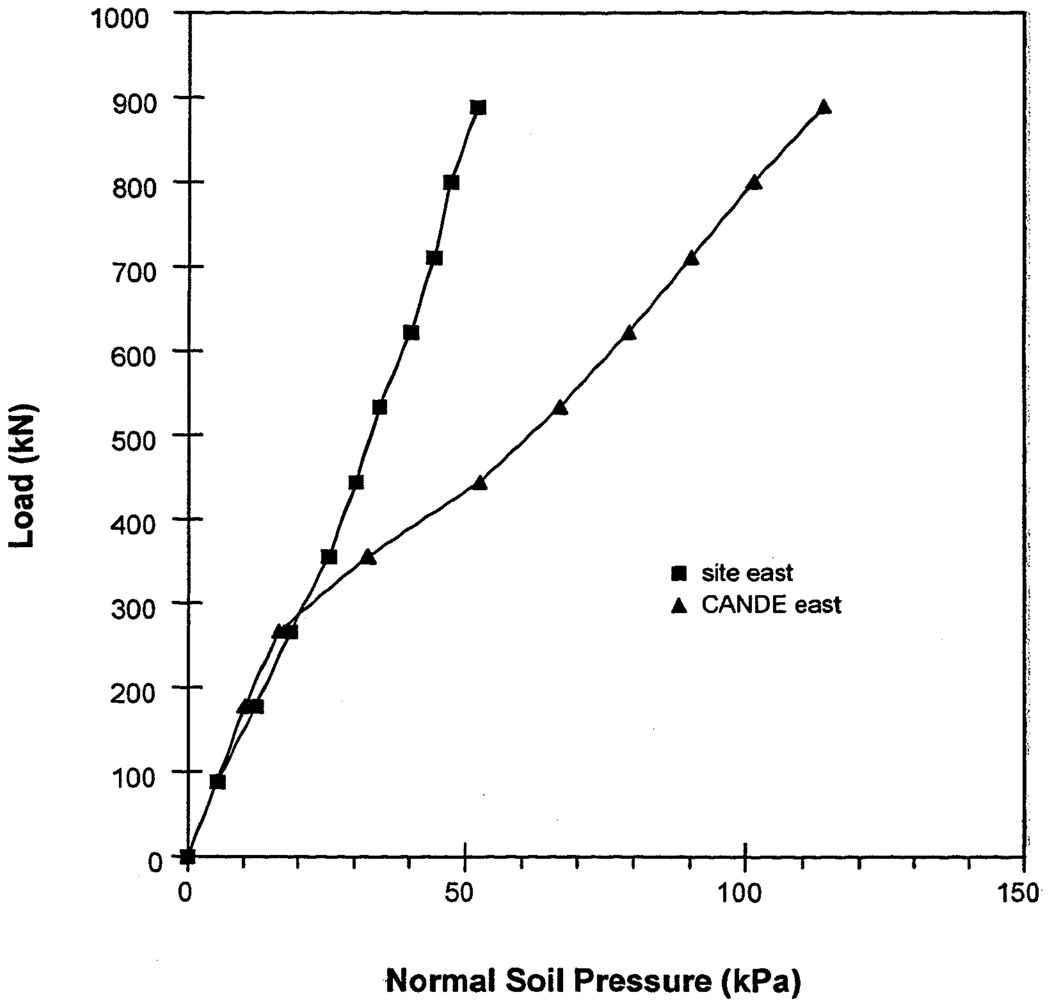

1000
900
800
700
600
500
400
300
200
100
0
Load (kN)
0
100
200
300
400
Normal Soil Pressure (kPa)
◇ site east
□ site west
▶ CANDE east & west

FIGURE 7



1000
900
800
700
600
500
400
300
200
100
0
Load (kN)
0
50
100
150
Normal Soil Pressure (kPa)
■ site east
▲ CANDE east

LEGEND TO FIGURES

Figure 1. Geometric properties of CON/SPAN test section: 11 m span x 2.74 m rise. (All dimensions are in millimeters.)

Figure 2. CON/SPAN test section shop drawing showing unit reinforcing and material requirements. (All dimensions are in millimeters.)

Figure 3. Schematic of test set-up and instrumentation of test section.

Figure 4. Finite Element Mesh used in analysis.

Figure 5. Graph of applied load versus vertical displacement at centerline of structure. Both the field-measured (site ◆) and analysis (CANDE ○) values are shown.

Figure 6. Graph of applied load versus normal pressure at the top of the test unit legs. The field-measured values for both sides of the culvert (◊ & □), plus the analysis values (▲) are shown.

Figure 7. Graph of applied load versus normal pressure at the bottom of the test unit legs. The field-measured (■) and the analysis values (▲) are shown.