NORTHWESTERN UNIVERSITY
Infrastructure Technology Institute

2000 Research Progress Report

January 15, 2001

Contents

Introduction

Northwestern University's Infrastructure Technology Institute funds research projects on an annual cycle. Proposals are solicited from principal investigators currently supported by the Institute during this cycle. Proposals from other Northwestern researchers are accepted and evaluated throughout the year. Researchers are required to report monthly on their progress at meetings of the Institute's Research Associates group. In addition, the Infrastructure Knowledge Manager works with each researcher to put news about research projects and research end-products on the Institute's Web site. This report constitutes a summary of progress for each Institute-funded research project for calendar 2000.

Analysis of the Performance of the Rehabilitation of the Chicago-State Subway Station and its Effects on Adjacent Structures

Principal Investigator: Prof. Richard Finno

Situation Description

In 1999, the Department of Transportation of the City of Chicago (CDOT) undertook the rehabilitation of the existing subway station at the corner of Chicago Avenue and State Street. Portions of the existing tunnel were demolished and the station itself was expanded. The attendant excavation presented a number of challenges, including excavating through 13 m. of soft to medium stiff glacial clay while minimizing associated ground movements so that damage to the adjacent St. Frances Xavier Warde School and Holy Name Cathedral would be minimized. The Warde School was founded on shallow foundations that were located within 1.3 m. of the wall of the excavation. The presence of the subway station and twin subway tubes restricted the methods of providing lateral support of the wall, prompting the use of both cross-lot braces and tiebacks.

Northwestern University and Wiss, Janney, Elstner Associates, Inc., were retained to monitor the ground deformations and structural responses of the surrounding buildings. The field performance data included soil deformations, pore water pressures, building movements, and support loads. Inclinometers measured lateral movements at five locations around the excavation. Data were obtained on a daily basis by Northwestern University during wall installation and excavation and at least on a weekly basis after the excavation had reached its final depth. Building movements were optically surveyed weekly during construction. Conditions at the site during construction are shown in Figures 1 and 2.

Figure 1. Excavation to First Tieback Level

Figure 2. Base and Mezzanine Slabs Placed

In 2000, the Infrastructure Technology Institute funded the first year of the proposed two year project, the purpose of which is to use the data obtained from the monitoring effort to check methods of predicting ground movements arising from supported excavations in soft clay, and to evaluate the soil-structure interaction between the adjacent buildings and the deforming soils. Damage to the Warde School occurred, and analyses of the detailed soil-structure interaction will provide information concerning levels of movement and *onset* of damage. The excavation for the subway renovation was completed and completely backfilled by May 2000. Inclinometer data for lateral movements and optical surveys for building settlements were obtained through May so that a complete record of the performance of the excavation support system could be obtained.

The support system performed as it was designed. The secant pile wall with its combined bracing system provided adequate support for the adjacent, shallow foundation-supported Warde School. As planned in the design, minor damage occurred to non-load bearing portions of the school. Maximum lateral soil movements and building settlements were predicted to be 32 mm., but the "accuracy" of the predictions was a result of compensating errors. Of the 38 mm. lateral soil movement, Figure 3 shows that 9 mm. occurred during wall installation, 16 mm. developed as the soil was excavated and 13 mm. occurred during tunnel demolition and station renovation as a result of creep and reduction of wall stiffness. Similar magnitudes of components of movements were observed at other monitored sections. Only about half the movements developed during excavation. The other components of movements are relatively small, but when the major design criterion is strict deformation control, the movements associated with wall installation and long-term effects become a significant portion of the total movements.

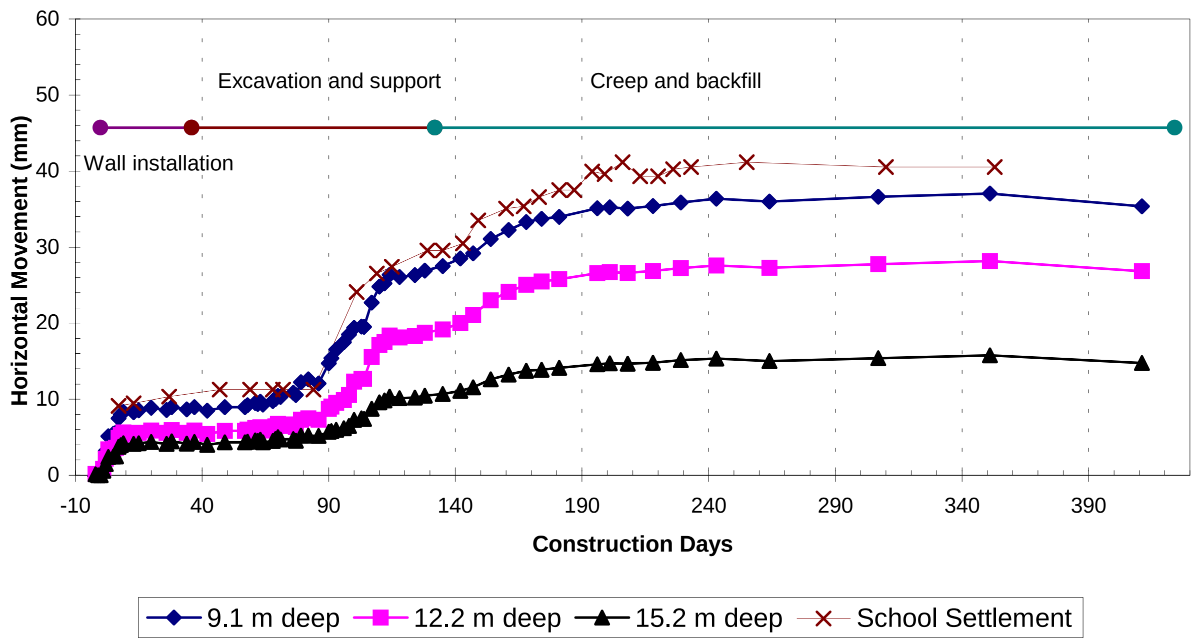

Figure 3. Movements at the Warde School

When distortions exceeded approximately 1/960, damage began to manifest itself in the non-load bearing portions of the school. Hence for a structure like the Warde School, a reinforced concrete frame supported on reinforced concrete beams and columns at interior locations and exterior masonry walls and concreter columns at the building perimeter, distortions would need to be limited to less than 1/1000 to preclude any damage to the building.

Progress

The laboratory evaluations of the stress-strain-strength responses of the three compressible glacial clay strata at the site are almost complete. In each layer, index property, consolidation, drained and undrained triaxial compression, and drained triaxial extension tests have been conducted. Three drained triaxial compression tests have been conducted in each stratum. These results are used to determine the effective stress soil parameters for use in the constitutive models representing soil behavior in the finite element analyses.

The finite element work has progressed significantly in the past year. An existing code developed by the US Geological Survey, called UCODE, has been coupled with the finite element code, JFEST, co-written by the Principal Investigator. This combination allows one to automatically optimize the input parameters to obtain the best fit for a specific output of the finite element code. The combination has already been used to find the single set of parameters that gives a best fit for the stress-strain and volumetric strain data from the drained tests and the stress-strain and pore pressure data from the undrained test from one of the compressible clay strata. The sensitivity to the various inputs is also a product of the codes. When applying this procedure to the analyses of the excavation, the parameters will be adjusted to provide the best fit to the lateral deformation data obtained from the inclinometers at various times during construction. Variables that will be optimized are (1) the soil parameters from at least 2 different effective stress constitutive models, (2) wall stiffness, and (3) construction procedure. Wall stiffness is a variable in these analyses for a number of reasons, including variable wall thickness resulting from construction variations, the time-dependent gain in strength of the grout, and the different grout mixes that were used by the contractor. Also the effects of the construction of the subway tunnel and station in 1940 will be evaluated numerically.

When completed, the major benefit of this numerical work is that one can update predictions based on field observations in a very short time. This quick turnaround is necessary if the procedure is to be adopted in practice when one must control the construction process to minimize ground movements. In the course of the work at the Chicago-State project, Northwestern was obtaining field data, processing it, and updating predictions of response to additional excavation by trial and error adjustments of the finite element parameters that best fit the observed field data. This cycle was at times done on a daily basis, and was possible only because of the number of students involved with the project. With the updated procedure, the numerical work that took as long as 8 hours, could easily be done in one hour, and thus become a practical tool for the profession.

Students

A number of students have worked, and are continuing to work, on this project and have been supported by Institute funds:

Kristi Kawamura completed her MS thesis entitled “Hardening Soil Parameters for Compressible Chicago Glacial Clays.”

Gilles Marchadier, from the Institute of Science and Technology at Grenoble, France, completed an internship at Northwestern University and wrote the report “Instrumentation and Numerical Simulation of the Chicago-State Excavation,” (in French).

Jill Roboski will soon finish her MS thesis that completes the laboratory evaluation of the compressible glacial clays.

Sebastian Bryson is working on his PhD and is focusing on the evaluation of the field data and the structural response of the adjacent school.

Michele Calvello is working on his PhD and is focusing on the finite element studies, especially the automatic updating of parameters based on observed field responses.

Publications

A paper, “Design and Performance of a Stiff Support System in Soft Clay,” summarizing the performance of the supported excavation has been submitted to the ASCE Journal of Geotechnical and Geoenvironmental Engineering. Several other papers are in preparation.

Evaluation of Capacity of Micropiles Embedded in Rock

Principal Investigator: Prof. Richard Finno

Current practice in many locales dictates that micropiles be designed for allowable stress of 12 ksi in the steel and 1600 psi in the grout, in addition to the restrictions imposed by the shear strength of the surrounding soil and rock. Past experience has indicated that when micropiles are installed in competent rock, the load deflection response is essentially linear up to the allowable load determined from the stresses in the pile. To evaluate the ultimate capacity of such piles and to justify use of a less conservative design approach, a series of axial load tests were conducted on micropiles installed in dolomite. This project is a joint effort between the Department of Civil Engineering at Northwestern University and TCDI, a specialty geotechnical contractor based in Lincolnshire, Illinois. The axial load tests were conducted from the floor of a quarry southwest of Chicago. A photo of the test section is shown in Figure 4.

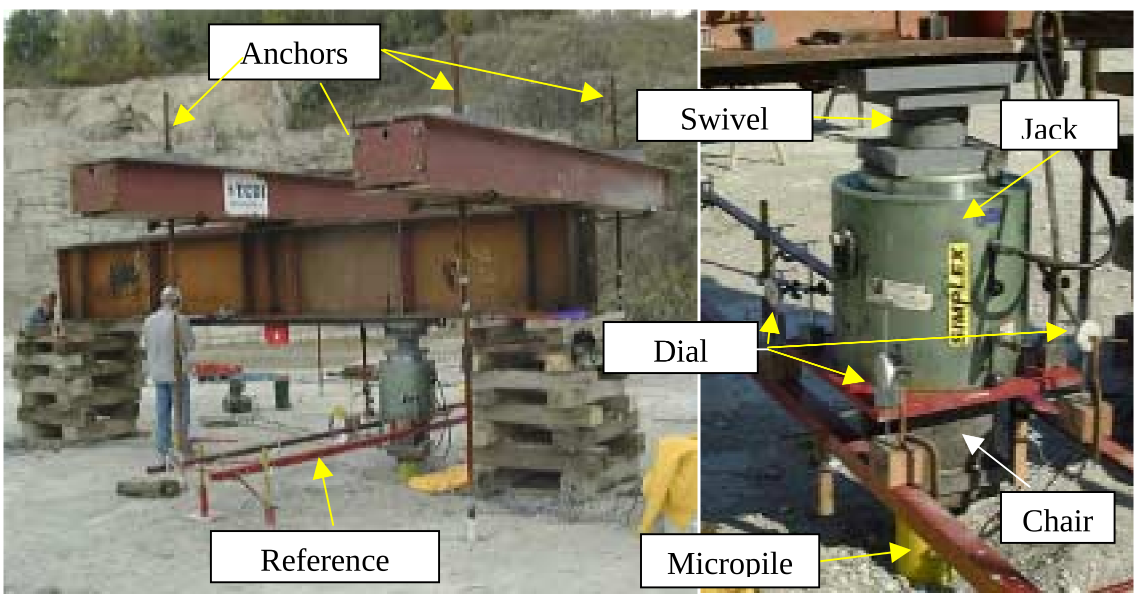

Figure 4. Micropile Test Section

The micropiles consisted of 178 mm. diameter piles with a wall thickness of 13 mm. The piles were drilled into rock with sockets that varied in length from 0.3 to 2 m., were tremie-filled, and then grouted with pressures of about 350 kPa. Axial compressive tests were conducted on piles instrumented with pairs of strain gages spaced every 0.6 m to determine axial load distributions and load transfer characteristics. Additionally, embedment gages were installed in the grout in two of the test piles. Photos of the instrumentation are shown in Figure 5. The longest pile was installed with its tip in an artificial “soft” bottom to precisely define the mobilized side resistance. These short lengths made it easier to instrument the piles and provided a direct measure of the increase in bearing capacity with embedment. The load transfer data provided by the instrumentation allowed the separation of the side resistance in the rock socket from the end bearing capacity.

Rock cores were drilled at each pile location to determine the quality of the dolomite. Bedding and joint plane orientations were noted in the field so their effects on rock mass strength can be estimated. The cores showed that the quality of the rock was quite variable. Compression and split tension tests were conducted on specimens of intact dolomite recovered from the cores. Compression tests were also conducted on specimens of the grout to measure the modulus and strength of the grout.

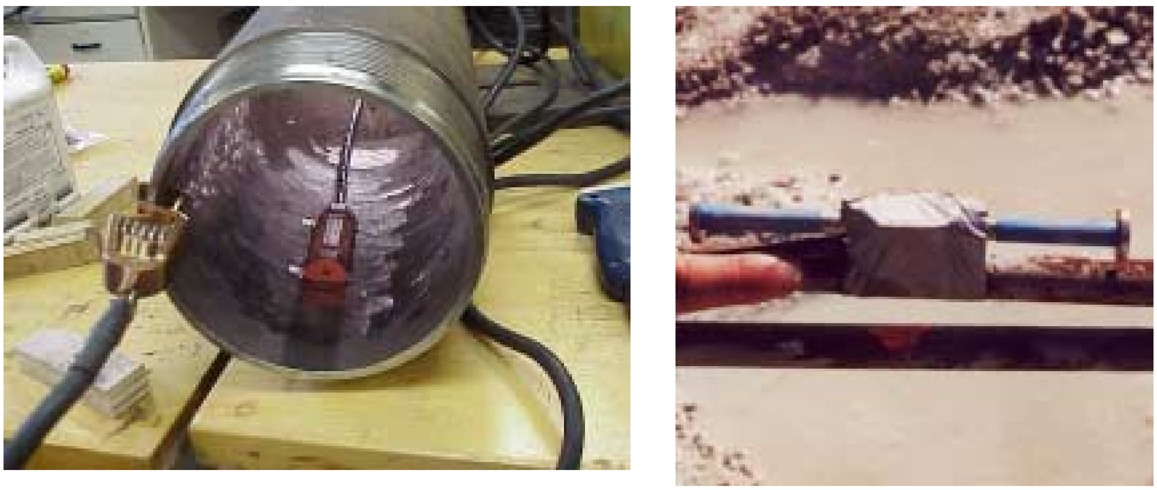

Figure 5. Strain and Embedment Gauges

Several load tests on 35 m. long micropiles in the downtown area of Chicago have been conducted. These micropiles were embedded in similar dolomite in which the quarry tests were performed. Axial load-deflection results from the load tests conducted to maximum loads of 400 kips at sites in the downtown area of Chicago are shown in Figure 6. Results of a typical test conducted at the Quarry site is shown in Figure 7. Loads as great at 1000 kips were applied without failure at the quarry site. These results suggest that the current practice based on structural considerations can be quite conservative, if the rock is competent. Load transfer through side friction within the rock socket is the dominant load transfer mechanism. However, the data suggested that the critical interface for determining the amount of side friction was that between the grout and the steel casing, and not the grout-rock interface. Comparison of the strains in the steel measured by the strain gages and that in the concrete measured by the embedment gages indicted that debonding between the grout and the steel casing occurred at relatively low axial loads. Further analyses of the load transfer data are needed to fully understand the load transfer mechanisms so that proper design procedures, or perhaps better micropiles, can be developed.

Note that TCDI provided the materials for the micropiles, installed them, constructed the load frame and conducted the axial load tests. Thus TCDI provided cost sharing in the form of materials, equipment and personnel. These costs were almost twice the funds provided by ITI. Northwestern University provided the electronic instrumentation needed to obtain the axial load distribution along the length of the rock sockets, collected the strain gage data during the load tests, and analyzed the results.

Benoit Paineau, a research assistant at Northwestern, completed his MS thesis, "Capacity of Micropiles in Dolomite." An abstract, "Load Transfer Characteristics of Micropiles in Dolomite," has been accepted for the 2002 International Deep Foundations Congress sponsored by the GeoInstitute of ASCE.

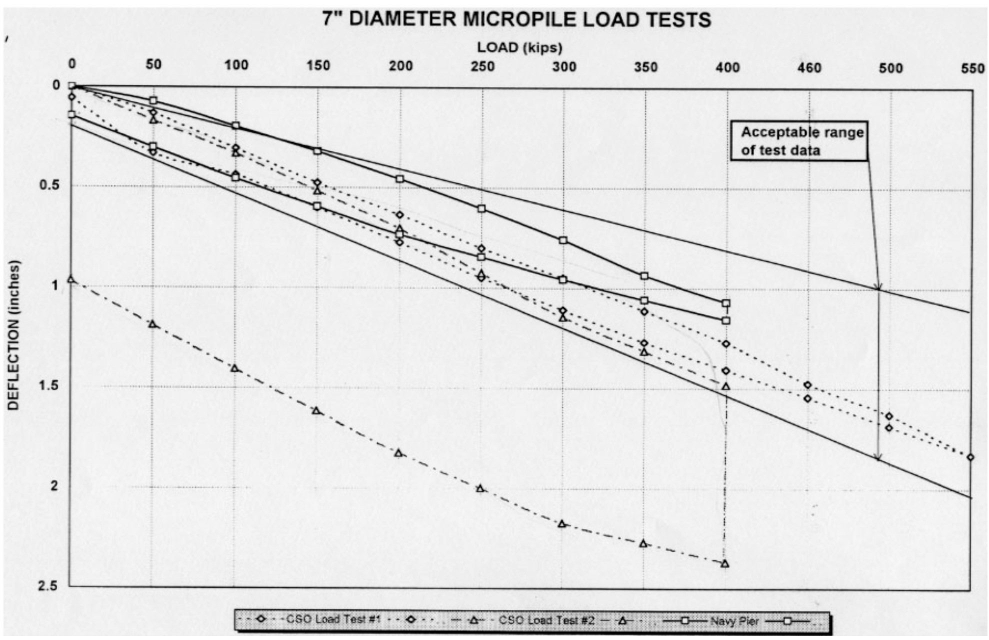

Figure 6. Results of Axial Load Tests at Downtown Chicago Sites

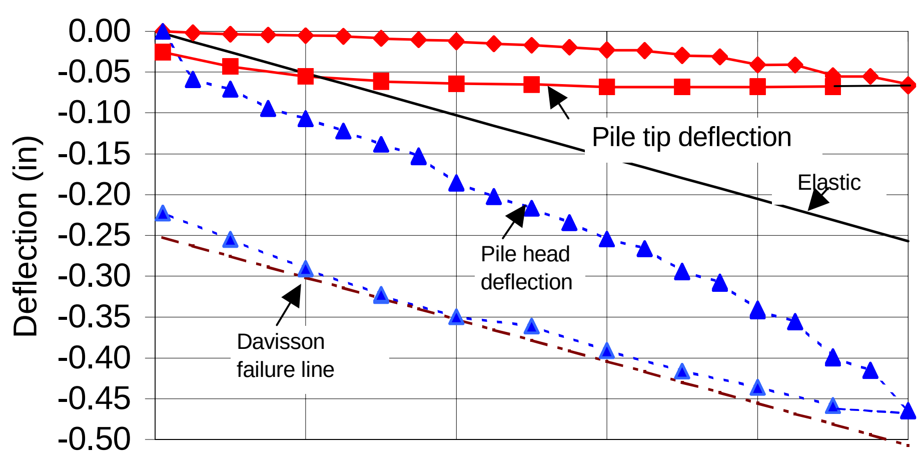

Figure 7. Results of Axial Load Tests at Quarry

Improved Condition Monitoring of Bridges:
Nondestructive Evaluation of Foundations

Principal Investigator: Prof. Richard Finno

The purpose of this project is to develop methods to non-destructively evaluate the condition of existing deep foundations and bridge piers. With previous support, a drilled shaft test section for non-destructive evaluation has been established at the National Geotechnical Experimentation Site (NGES) at Northwestern University. Experimentation at this test section and subsequent analysis and numerical simulation have defined the limits of the ability of the impulse response technique to evaluate damage to drilled shafts in both accessible and inaccessible head conditions. A multiple geophone method has been developed which minimizes the effects of the surface wave reflections from intervening pile caps at the NDE test section. The impulse response technique with and without multiple geophone arrays has been used in the field at a number of bridge sites. A theory based on guided waves, describing the relation between frequency and group velocity of frequency-controlled excitations, has been developed to allow higher frequencies to be used to evaluate shafts, and, consequently, to identify smaller defects than possible with conventional techniques.

The work this year focused on development of an experimental system that utilizes the guided wave approach, and continued field testing of conventional non-destructive testing methods.

Develop experimental system for guided wave tests

With a theoretical solution to the guided wave problem for wave propagation along a cylindrical pile in hand, and a prototype experimental system for inducing high frequencies bursts of energy available, we conducted the following tests to verify the theoretical solution and evaluate the test equipment:

1. Laboratory verification tests of the system. We tested prototypes piles in the laboratory in a free condition to verify the theory for higher modes of vibration. See Figure 8 for the testing arrangement. When testing a pile in the free condition in the laboratory, many modes of vibration propagated, even when the excitation consisted of one frequency. Propagating modes were identified both by comparing the observed propagation velocity with the theoretical results and by using short-time fast Fourier transform analyses.

2. Field verification test on prototype piles installed at the Northwestern NGES. These piles were made with different concrete (or grout) mixes so that each would have a different modulus, and hence the ratio of shear wave velocity of the pile to the soil would vary for each of the three piles. Also the piles were either 12- or 18-inches in diameter. In the limited amount of work done to date, we have found that only the second mode propagates at higher frequencies (15 kHz).

Figure 8. Experimental Set-Up for Guided Wave Tests in Laboratory

Continued field testing of conventional non-destructive testing methods

We conducted impulse response tests on the drilled shafts at the Amherst NGES as part of the prediction symposium held in conjunction with the ASCE Specialty Conference on Performance Confirmation of Constructed Geotechnical Facilities held in April 2000. Figure 9 shows our team conducting the tests at the Amherst site.

Figure 9. Nondestructive Testing at Amherst NGES

These nominally 14-m-long drilled shafts were constructed with anomalies, the nature and number of which were unknown when the impulse response tests were conducted and the analyses made. The planned anomalies included necking, voids, caving and soft bottoms. Our predictions were based on conventional mobility plots, impedance logs and comparisons with numerical simulations. Besides Northwestern, five firms who commercially nondestructively test deep foundations made predictions. Our predictions were as good as, or better than, all those based on surface reflection methods.

Students

Hsiao-Chao Chou has assisted him and is expected to complete his PhD dissertation this summer.

Helsin Wang has joined the team, and will pursue a PhD degree.

Publications

The following papers were published this past year:

Gassman, S.L. and Finno, R.J., "Cutoff Frequencies for Impulse Response Tests of Existing Foundations," Journal of Performance of Constructed Facilities, ASCE, Vol. 14, No. 1, February 2000, p. 11-21.

Finno, R.J., and Chao, H.-S., "Nondestructive Evaluation of Drilled Shafts at the Central Artery/Tunnel Project, Proceedings, Structural Materials Technology IV: an NDT Conference, Atlantic City, New Jersey, Feb. 2000, 81-88.

Gassman, S.L. and Finno, R.J., "Anomaly Detection in Drilled Shafts," Proceedings, National Geotechnical Experimentation Sites, Geotechnical Special Publication 93, ASCE, J. Benoit and A.J. Lutenegger, eds. , 2000, p. 221-234

In addition, two papers have been submitted to archival Journals:

Finno, R.J., Popovics, J.S., Kath, W.L. and Hanifah, A.A., “Frequency Equation for Cylindrical Piles Embedded in Soil,” Journal of Engineering Mechanics, ASCE.

Finno, R.J., Popovics, J.S., Hanifah, A.A., Kath, W.L., Chao, H.-C., and Hu, Y.H., “Guided Wave Interpretation of Surface Reflection Techniques for Deep Foundations,” Italian Geotechnical Journal.

The following abstract has been accepted for the 2002 International Deep Foundation Congress sponsored by the GeoInstitute of ASCE:

Finno, R.J., Chou, H.-C., and Gassman, S.L., “Non-destructive Evaluation of Drilled Shafts at the Amherst NGES Test Section.”

Failure Analysis and Life Cycle Management of Steel Bridges

Principal Investigators: Prof. Brian Moran, Prof. Jan D. Achenbach
Graduate Student: David Houcque

Objective

The thrust of the project is to develop an understanding of failure mechanisms in pin-hanger connections in steel bridges and to develop guidelines for the assessment of the structural integrity of the connections. A typical pin-hanger connection is shown in Figure 10. The connection serves as a thermal expansion joint in an intermediate span of the bridge. When functioning as designed for, the joint rotates freely under thermal expansion or contraction. Two potential failure mechanisms are being considered: 1) Due to corrosion and the introduction of "pack rust" into the mechanism, the connection may partially or fully "freeze" thus inhibiting the free rotation of the joint. This can lead to a large torque on the pin with possible plastic yielding and failure of the pin. 2) Cycling loading (due to daily temperature fluctuations) of the pin (in the freely rotating or partially frozen conditions) may cause the growth of fatigue cracks and the emergence, in time, of a fatal flaw (with stress intensity factor exceeding the fracture toughness).

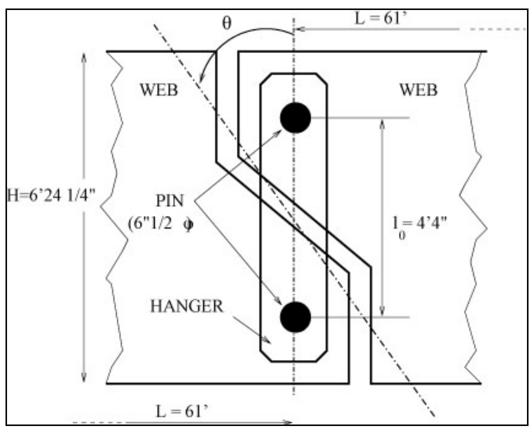

Figure 10. Schematic Representation of Pin-Hanger Type Connection

We have carried out a finite element analysis of a typical connection to examine the first of these mechanisms as described below.

Technical Progress

To investigate the effect of freezing of the pin-hanger connection (failure mechanism no. (1) above) we have carried out a series of finite element analyses (using the ABAQUS finite element code) of the joint under mechanical and thermal loading. A realistic simulation of the pin-hanger connection requires a three-dimensional analysis allowing for contact and friction between the various parts of the mechanism. Material properties were taken to be those of ASTM A36 structural steel with Young's modulus (E) of 200,000 MPa (29,000 ksi) and Poisson's ratio (ν) of 0.3. The yield and ultimate strengths of the material are $\sigma_Y = 30$ ksi and $\sigma_{UTS} = 58$ ksi, respectively. The thermal expansion coefficient is taken to be $\alpha = 6.5\times10^{-6}/^{\circ}\mathrm{F}$.

The finite-element mesh in the vicinity of the connection is shown in Figure 11. Three-dimensional brick (8-node) elements are used in the analysis and the model has 73,000 degrees of freedom. The bridge span is 122 ft with the joint in the center. The supports are taken to be built-in (it may be worthwhile to consider modified support conditions for comparison).

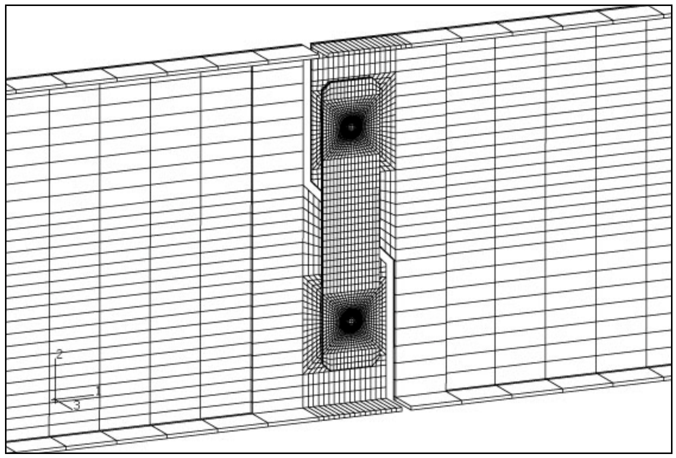

Figure 11. Finite-Element Mesh (Pin-Hanger Detail)

Thermal Expansion

To verify the finite element model of the rotating pin-hanger connection, including various aspects of contact between the parts of the mechanisms, a thermal expansion analysis was carried out. The bridge is subjected to uniform temperature changes. At the reference temperature, $\Delta T = T - T_o = 0$, the connection is unrotated. With an increase/decrease in temperature, the joint rotates counterclockwise/clockwise. A simple thermal strain analysis for small rotations gives the expression $\theta = 2\alpha \Delta T L / l_0$ for the joint rotation, where L is the half-span and l_o is the distance between the upper and lower pin centers. Note that this expression is linear in the temperature change ΔT. The results of the finite element simulation are compared with the values given by this expression in Table 1 and are seen to be in excellent agreement. This validates the finite element model of the joint and the contact algorithm employed in the ABAQUS code.

Table 1 – Pin-hanger rotation angle (θ) – Comparison between analytical solution and finite-element prediction

ΔT	θ	θ_{FEM}
$-34^0 C$	-0.658^0	-0.662^0
$-20^0 C$	-0.387^0	-0.389^0
$20^0 C$	0.387^0	0.389^0
$50^0 C$	0.968^0	0.974^0

External Load

An analysis of the bridge under the design external load of 100,000 lbf was carried out at the reference temperature (50 F or 10 C). At this temperature, no thermal stresses are induced and the analysis provides a baseline for subsequent comparison. The load was applied at the top of the web at the pin-hanger connection. Under external load alone, the equivalent stress (Mises) was found to be 115 MPa $(0.46\times\sigma_Y)$ at the top pin in the region of contact between the pin-plate and the top hanger.

Thermal and Mechanical Load in Frozen Condition

Several analyses were carried out to explore the effects of friction in the joint. A Coulomb friction model is used in conjunction with the contact algorithm in the ABAQUS code. We model the limiting case of a fully "frozen" joint (in which the most severe stresses would be induced) by having full stick (or rough friction) between the pin and the web-plate, pin-plate and hanger-plate surfaces. The maximum von Mises stresses for different temperatures are shown in Table 2. The maximum stress occurs in the top pin in the region of contact between the pin and the hanger (at about the 9 o'clock position). It can be seen from the table that, under the fully frozen condition, the yield strength is exceeded even for moderate temperature changes. A word of caution is necessary here. The analysis was a linearly elastic one. It is safe to say that the yield strength is exceeded (perhaps even significantly) but a full elastic-plastic analysis is required to obtain accurate values of the stress once yield is exceeded and to determine if collapse/failure would indeed occur under these conditions. This will be carried out in the next phase of the project.

Table 2. Maximum von Mises stresses in pin for different temperatures

$T(^0F)$	σ_{FEM}	σ_{FEM}/σ_Y
$T_0 = 50$	115.84	0.46
68	75.41	0.30
86	241.32	0.96
110	466.11	1.86
32	284.33	1.14
14	453.79	1.81
-10	679.86	2.72

Progress

Graduate student David Houcque has been supported on this project. A post-doctoral student Dr. Shaowei Hu has been partially supported. He is working on the development of the extended finite element method and probabilistic methods for assessment of the fatigue failure mechanism. A paper on our work to date (Houcque, Moran and Prine) is being prepared for publication and presentation at conferences. The next phase of the project will follow up on the frozen joint analysis and explore the fatigue crack growth aspects.

Further Commercialization of 70-ksi NUCu Steel

Principal Investigators: Prof. Morris E. Fine, Semyon Vaynman, PhD

Retrofitting of I-55/I-70 Poplar St. Bridge with NUCu 70W Steel

During the late spring of 2000, 88,000 lbs. of one-inch-thick plates of NUCu 70W steel were used in the retrofit of the I-55/I-64/U.S.-40 Poplar Street Bridge complex over the Mississippi River in St. Clare County, IL near St. Louis. This bridge that is located near the Madrid fault had a cracked member. High strength steel was required because of weight limitations and high fracture toughness was required because of seismic considerations. The steel was cast and rolled by Oregon Steel Mills, Portland Oregon. For this application the NUCu 70W steel was normalized and aged after rolling. As measured by Oregon Steel Mills and Missouri Fabricators, the yield strength was 75 Ksi and the Charpy fracture energy at -10^{o}F was 95 ft-lbs. The Illinois Department of Transportation (IDOT) obtained funding to pay for the use of our experimental steel from the FHWA Innovative Bridge Research and Construction Program authorized in the Federal TEA-21 program. Chris Hahin of IDOT wrote the proposal to FHWA with our assistance. Additional plates for this application were fabricated from the ASTM A709 HPS70W Q&T steel previously developed under the AISI/Navy/FHWA program. The retrofit for this bridge was designed by Wiss, Janney, Elstner & Associates, fabricated by Missouri Fabricators and installed by St Louis Bridge Co. Figure 12 is a photograph of this bridge with the attached NUCu steel plates.

Proposed Use of NUCu Steel for the New LaSalle, Illinois Bridge

A new bridge at LaSalle, IL has been designed and contracts are expected to be let in June 2001. The consultant has specified girders with 3-inch-thick flanges and 1-inch-thick webs 2.7 to 3 ft. wide. The girders are to be fabricated with 70W steel. Chris Hahin of IDOT, who has been involved in the development of NUCu steel almost from the beginning, has recommended ASTM A709 HPS70W Q&T steel for the flanges and our, NUCu 70W, steel for the webs. Unfortunately we have no data or experience with our steel rolled to 3-in. thick plates so it cannot be specified for the flanges at this time. This is a large application of NUCu steel and would require several commercial heats. Chris Hahin, Semyon Vaynman, and Morris Fine met with the five plate mill engineers at the US Steel Company's Gary Works to discuss steel production. They very much wish to manufacture NUCu steel and are hoping to get an order. In addition to Oregon Steel Mills, USS is another source of NUCu steel. USS Company has experience with NUCu steel. In the past they produced three experimental heats of our steel.

Proposal to Include NUCu Steel in ASTM A709 Specification

At this time the major barrier to use of NUCu steel is that it is regarded as experimental steel and is not included yet in the ASTM A709 specification for bridge steels. Chris Hahin is now on the ASTM sub-committee and he plans to propose inclusion of our steel in the ASTM A709 specification since two commercial heats have been already produced at Oregon Steel Mills. He has volunteered to draft and submit a proposal for ASTM sub-committee meeting in May 2001. Since there is much interest in an improved 50W steel, he has recommended preparing a dual proposal for 50 and 70-Ksi yield steels. We already prepared a data set listing producers, compositions and mechanical properties of our steel. This data set includes three manufacturers (Inland Steel, USS and OSM) and 8 steel heats with several different heat treatments. The outstanding Charpy fracture energy at cryogenic temperatures for NUCu steel is shown in the data set. NUCu steel is attractive to steel companies because of its excellent mechanical and weathering properties combined with the simpler processing than for ASTM A709 HPS70W Q&T. This gives the steel companies a competing edge.

Weatherability

As we reported previously, NUCu steel and other weathering steels were subjected to an ASTM accelerated corrosion laboratory test at Bethlehem Steel Company. The results of this test were previously shown to correlate very well with outdoor exposure tests. Our steel substantially outperformed all other weathering steels in this test. The comparison including A36 structural steel is shown in the following bar chart (Figure 13). Based on large data sets for long time exposure, algorithms were developed to predict weight loss from steel composition after long time exposure at Pittsburgh, Pennsylvania by H. Townsend of Bethlehem Steel Company and at Kure Beach, North Carolina by us. The weight losses predicted for the steels in the test program are also given on the bar chart and the correlation with the relative ratings of the steels in the accelerated test is good. Of course actual long time exposure in weathering tests are needed and these including our steel are underway in an ASTM sponsored project. Early test results are not in yet.

The algorithms mentioned above allow design of even better weathering steels. We suggested such a development to Bill Wright of FHWA and Tom Montemorano of the Navy (members of the AISI/FHWA/Navy Steering committee on high performance structural steels). The former has invited us to submit a proposal and also told us about the need for an improved 50W steel. For the 50W grade our previous results showed that adding 0.1 % Ti reduced the yield stress to 60 Ksi by tying up the C as TiC but gave a remarkable high Charpy fracture energy at –80^{o}F. These data are for NUCu steel air-cooled after hot rolling. Ti alloyed NUCu steel may be a big winner because of its high fracture energy and improved weathering resistance.

Other Commercialization Activities

We are in discussions with Chicago DOT engineers about using our steel for painted girders instead of painted A36 steel in bascule bridges. There should be less salt corrosion under the paint and we have begun planning corrosion tests to demonstrate this effect. We have been in contact with DOT engineers in several other states and some have shown interest. Other applications besides bridges are being explored.

Figure 12. Retrofitted I-55/I-64/US-40 Poplar Street Bridge Complex over the Mississippi River, St. Clare County, Illinois

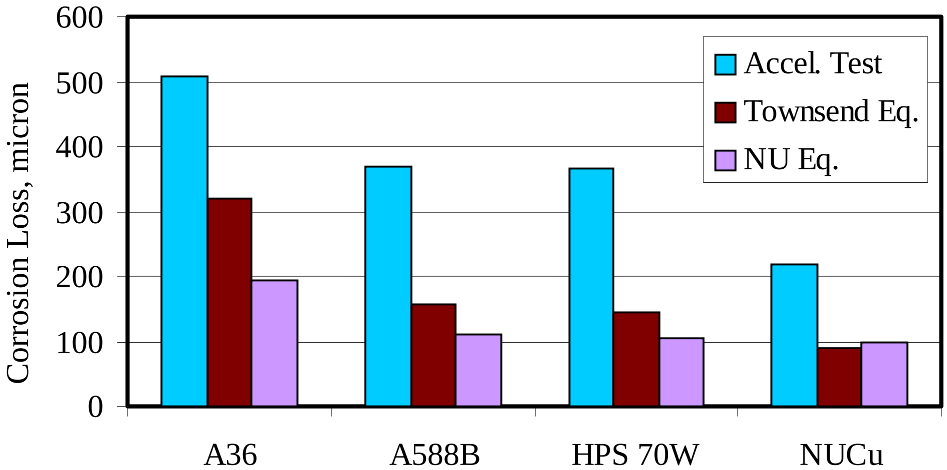

Figure 13. Corrosion Loss in Accelerated Test of NUCU Steel and Predicted Loss for Other Steels

Commercialization of Time-Domain Reflectometry (TDR) Measurement of Soil Deformation in Support of Improved Condition Monitoring for Bridge Management

Principal Investigator: Prof. Charles Dowding

Technical Accomplishments

Interpretation of Cable-Grout Composite Sensitivity in the Field

"TDR and slope inclinometer response at three sites has the potential to reveal the in situ sensitivity of cable-grout composites to localized shearing in soft soils."

This work has been completed and results are being published through a variety of mechanisms. A paper, "Comparison of TDR and Inclinometers for Slope Monitoring" (with K. M. O'Connor) summarizes some of these findings in an ASCE Geotechnical Special Publication #52, Field Instrumentation. Another paper, "Detection of Shearing in Soft Soils with Compliantly Grouted TDR Cables" is currently under preparation.

Complete Laboratory Shearing of Special and Commercial Large Diameter Braided Cable

Initial testing was conducted to explore the extremes of the possibility matrix. This task remains to be completed as the research assistant left the university midway through the year. As a result monies remain in the account for this task.

Develop a Truly Remotely Operable Instrument Package for IDOT Site

A cellularly communicating, solar powered instrument system that can employ the HYPERLABS pulser is required to reduce the enormous start-up costs of remote monitoring. This task was also not completed as a result of the departure of the research assistant and work overload of the ITI instrumentation specialists. Progress was made toward this goal through the installation of the next stage of remote monitoring equipment at the Indiana State Road 62. This installation -- a joint effort with the ITI instrumentation group -- involves deployment of the HYPERLABS pulser, which will allow continued development of the low power consumption system.

Install Mine Subsidence Monitoring System

This instrumentation system allows ITI to assist PennDOT as it copes with the planned subsidence of I 70 by some THREE (3) FEET. This task was successfully completed and a summary article has been written with GeoTDR, and PennDOT for presentation at the Jan 2001 TRB meeting in Washington D.C. This paper, "Real Time Monitoring of Subsidence Along I-70 in Washington, Pennsylvania" has been listed as one of few of the hundreds given that is recommended for their practical importance. This project was of critical significance and involved some $400,000 of PennDOT instrumentation to compliment the ITI expenditures.

Install Pier Deformation Monitoring System on I 57 over the Mississippi for IDOT

While this project is not TDR related, it was planned during the reconnaissance for remote monitoring sites and illustrates the potential of district by district visits with state bridge and geotechnical engineers. Again this task was also not completed as a result of the departure of the research assistant and work overload of the ITI instrumentation specialists. The instruments were purchased but not installed and await another opportunity.

User Community Involvement in Addition to the Bridge NDE User's Group
TDR specific user community involvement was fostered through five mechanisms: papers at workshops and specialty sessions, demonstration projects, TDR-L Email listserv, development of the TDR 2001 Symposium, and installations and consulting by Dr. O'Connor of Geo TDR. ITI and GeoTDR personnel have made presentations at the following conferences:

1) The DOT Structural Materials Technology IV (NDT) Conference in Atlantic City in March 2000

2) The ASCE Geo-Institute Specialty Sessions on Field Instrumentation in Denver in August 2000

3) The Midwest Bridge Inspectors' Meeting in Indianapolis in November

4) FHWA Specialty Conference on Geophysical Instrumentation in St. Louis in December 2000

Demonstration projects have been summarized elsewhere. They have mainly involved rock or stiff soils and therefore soil sites are a high priority. The LTV and CTA sites and some horizons in the INDOT sites represent unique opportunities.

The TDR listserv, operated by ITI, continues to serve some 150 to 200 TDR suppliers and consumers. Provision of this communication channel maintains ITI's preeminence in TDR technology. Details can be found at

http://www.iti.northwestern.edu/tdr/index.html

Indirect support of Dr O'Connor's efforts to build GeoTDR, a company that specializes in TDR instrumentation, has been instrumental in developing ITI sponsored demonstration projects. For instance, GeoTDR installed the cables for the PennDOT project. Without his assistance, PennDOT would not have been able to develop their alarm system. GeoTDR was also able to meet with Florida DOT officials about use of TDR equipment for surveillance of sinkhole-induced subsidence.

Finally, the user community has been engaged by the interaction necessary to organize and plan for the TDR 2001, the Second International TDR Workshop and Symposium at Northwestern University. So far some 60 papers have been received for publication in the proceedings. In addition, three practical short courses are currently being planned for the gathering. Details can be found at

http://www.iti.northwestern.edu/tdr/tdr2001/index.html

Publications

1) " Real Time Monitoring of Transportation Infrastructure w/ TDR Technology" (w/ K.M. O'Connor), Proceedings of Structural Materials Technology IV: An NDT Conference, Technomic Publishing Co., Lancaster, PA, 2000

2) "Comparison of TDR and Inclinometers for Slope Monitoring" (with K. M. O'Connor) ASCE Geotechnical Special Publication #52, Field Instrumentation, August 2000.

3) "Real Time Monitoring of Infrastructure using TDR Technology: Case Histories"

4) "Real Time Monitoring of Infrastructure using TDR Technology: Principles" (with K. M. O'Connor) Proceeding of the FHWA International Conference on Applications of Geophysical Technologies to Planning, Design, Construction and Maintenance of Transportation Facilities, St. Louis in December 2000.

Educational Accomplishments

Graduate Students

William Bergeson, MS student. Gathered last data from field sites and began to develop finite element model of cable-grout-soil composite interaction.

James Blackburn, MS/PhD student. Will be assuming responsibility for operating Indiana State Road 62 TDR site

Undergraduate Students

Michael Babik, Senior. Is assisting with the planning and administration of the TDR 2001 Symposium

Commercialization of Instrument for Micro-Inch Measurement of Crack Width in Support of Continuous Remote Monitoring for Bridge Management

Principal Investigator: Prof. Charles Dowding

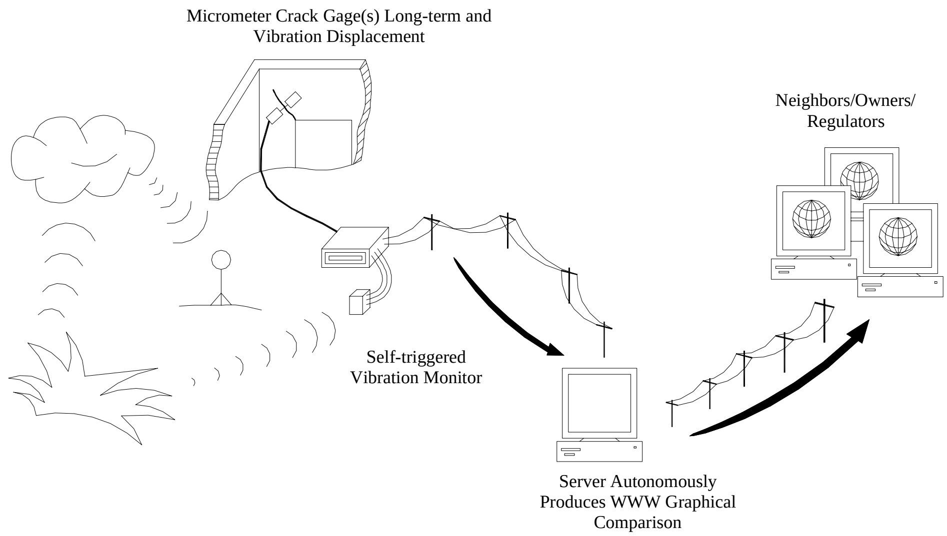

Figure 14. Autonomous Crack Comparometer: Automatically produces graphical comparisons of vibratorally and environmentally-induced crack displacement, which are accessible to interested parties via the Internet.

Technical Accomplishments

Complete Study of Optimal Crack Width Sensor

Effects of long-term electronic drift and temperature sensitivity on micro-inch measurement systems must be determined to ensure proper measurement over time spans of many months. Work under this task has been summarized in Michael Louis's MS Thesis, "Autonomous Crack Comparometer: Stage II" completed in early December 2000. This chapter compares response of five different gages: three eddy current gages, an LVDT, and an optical device. Use of a null gage, suggested by Geosonics our development partner, diminishes the impact of these effects.

Integrate Major Components of System

Completion of the stage 1 prototype by February should provide the platform to integrate the four major components of the system. This task was completed and reported in Damian Siebert's MS Thesis: "Autonomous Crack Comparometer" and an article by Dowding and Siebert, "Control of Construction Vibrations with an Autonomous Crack Comparometer" published in the Conference of the European Federation of Explosives Engineers in September. The article in PDF format and PowerPoint slides from Siebert's thesis can be accessed through Autonomous Crack Comparometer under the current projects heading on the ITI web site:

http://www.iti.northwestern.edu/research/c_projects/dowding/acc.html

Complete Writing Data Analysis Software

This software will discriminate two types of data: 1) no vibration or long term and 2) vibratory. Stage I deployment (Sheridan Rd House -- Siebert MS Thesis) allowed discrimination of household activity vibration from long-term effects. Stage II deployment (Franklin WS House -- Louis MS Thesis) allowed discrimination of ground motion vibration from long term effects. Stage III, as yet unattempted, will require that vibratory events from household activity be differentiated from those caused by ground motion.

Complete Writing Internet Software

The full Internet front end of the project will be a project in the Freshman Design and Communication course for the winter and spring quarters. This front end was completed and described in Damian Siebert's MS Thesis: "Autonomous Crack Comparometer." It has been slightly modified for Stage II, but a good deal more refinement is required. The Internet system can be accessed at the ITI Crack Monitoring Website:

http://iti.birl.northwestern.edu/acm/

Build Prototypes 1 and 2

Equipment for the Stage 1 prototype has been ordered and it should be built and installed in the test structure by the end of January 2001. Both of these prototypes have been constructed and described in Siebert's and Louis' MS Theses.

Assess Performance and Commercial Potential

These two tasks are scheduled to be undertaken in the second year. While no formal assessment has begun, meetings with quarry personnel at the Milwaukee site will be held in mid January 2001.

Reports

One article, "Control of Construction Vibrations with an Autonomous Crack Comparometer" was published in the Conference of the European Federation of Explosives Engineers in September. Another article, "A Radical Approach to Addressing Blasting Complaints," is being prepared for publication in Aggregate Manager, which is sent to managers of quarries throughout the United States

User Group Interaction in addition to the Bridge NDE Users Group

A small, specific, and informal user group has been developed. It consists of the President and chief engineer of Geosonics and two potential demonstration customers such as the owners of quarries in Miami, Florida and Milwaukee Wisconsin. As described above, individual meetings are being scheduled in the first quarter of 2001 Presentations were made at several locations to assess reaction to this thrust. In January a presentation entitled " A Radical New Approach to Vibration Monitoring and Control" was made at the 3rd Biennial Blasting Vibration Technology Conference, in Key West Florida. In September, the paper, "Control of Construction Vibrations with an Autonomous Crack Comparometer" was presented at the Conference organized by the European Federation of Explosives Engineers in Munich GR. In December, the concept was mentioned in discussions following presentation of a paper "Effects of Vibrations from High Speed Trains on Structures, Instruments, and Humans" at a European conference on train-induced vibrations.

Publications

1) "Autonomous Crack Comparometer" (D. Siebert) Master of Science Thesis, Department of Civil Engineering, Northwestern University, June 2000.

2) "Control of Construction Vibrations with an Autonomous Crack Comparometer", (Dowding, C.H. and Siebert, D.), Proceedings of the 1st world Conference on Explosives and Blasting Technique, Munich GR. A.A. Balkema, September 2000.

3) "Autonomous Crack Comparometer: Stage II," (M. Louis) Master of Science Thesis, Department of Civil Engineering, Northwestern University, December 2000.

Educational Accomplishments

Graduate Students

Damian Siebert, MS student. Developed (along with Dan Marron and Dave Kosnik) the Stage I prototype, wrote a MS thesis, and coauthored a paper describing the Stage I prototype.

Michael Louis, MS student. Developed (along with Dan Marron and Dave Kosnik) the Stage II prototype and wrote a MS thesis describing the Stage II prototype.

Laureen McKenna, MS student. Will focus on the final development of the Stage II prototype

Undergraduate Students

Dave Kosnik, Sophomore at Northwestern University. Has been working with the ITI/ACC team since the summer before his Freshman year to develop Java server side programs that are critical to the success of this project.

Matt Kotowsky, Sophomore at the University of Illinois. He has joined the team to speed the development of server side programs

Three other Freshmen Northwestern University Students who (along with the then Freshman Kosnik) developed the first Autonomous Crack Comparometer web site as a "real world" design project in the Engineering Design and Communication course.

Portability of Concept

This project has led the way to a new concept of Internet broadcast of instrumentation response for public consumption. Software developed for this thrust will be transportable to other types of instrumentation on bridges, which may eventually lead to Internet presentation of the response of ITI instruments around the country. Such Internet presentation provides a unique method of public interaction and education. However, critical to the realization of this public interaction is the expansion of resources expended in the area of knowledge management and server programming.

Televideo Conferencing to Facilitate Interaction between State DOT Staffs

Principal Investigator: Prof. Charles Dowding

ITI is exploring the use of the high speed Internet2 as an inexpensive means of interacting without traveling. Many state DOT personnel find it difficult to travel outside their own state. This travel restriction has inhibited interaction across state boundaries. For instance, the semi-annual meeting of bridge inspectors holds its meetings in different states to ensure that all inspectors can attend at some tome in the multi-year cycle of meeting places.

This new Internet technology (protocol h.323) replaces the telephone connectivity technology (h.320) with the Internet and thus decreases connect charges from some $100 per hour to $0. That is not an error: the connect cost is zero. Furthermore, interacting group conference rooms can be established with as little capital investment as:

Internet Connection	(assume exists)	$0
Large screen Television		400
Portable Projector	(assume have, not dedicated)	0
450+ Mhz Computer	(assume have, not dedicated)	0
Polycom Voice-Activated Camera		4200

Total Cost		$4600

ITI along with the Civil Engineering Department has embarked upon a multi stage demonstration program to explore uses of this technology. Costs are shared. The Civil Engineering Department has contributed some $4,000 as has ITI. Several limited, in-house demonstrations have been undertaken. The system has been set up in a faculty office to determine optimal equipment for a presentation by a single contributor. It has also been set up in the Civil Engineering Conference Room to determine the optimal configuration for group interaction.

These in-house demonstrations have led to two public demonstrations: one has been held and the second is planned. The first demonstration involved a remote presentation from Northwestern at a meeting of the Midwestern Bridge Inspectors Meeting in Northwest Indiana. This interaction was well received and indicated that the system works with only a T1 rather than fiber connection. It also validated the premise that the system can be established in any conference room with an Internet connection.

A second presentation is planned in conjunction with an ITI short course in instrumentation. Those unable to attend could enter the conversation from centers with h.323 equipment. Specifically, it is anticipated that two groups will participate as satellites: WisDOT and OkDOT as their state headquarters is located near to a research university campus that will have access to a high speed internet connection.

Should these demonstrations prove successful, ITI will embark upon a program of assisting state DOT's to establish their own conference facilities.

Nondestructive Testing and Evaluation of Bridges: Continuous Remote Monitoring

Principal Investigator: David Prine, Infrastructure Technology Institute
Contributing Investigators: Daniel Hogan and Daniel Marron, ITI

During the past 16 months the ITI Bridge NDE group has continued to work with our two most important technology deployment partners, the California Department of Transportation (CalTRANS) and the Wisconsin Department of Transportation (WisDOT) while adding additional partners including the Indiana Department of Transportation (InDOT). Our work has focused on continued development, demonstration, and introduction to practice of innovative continuous remote monitoring techniques and equipment for bridges and other infrastructure. Additionally the involvement of the group with faculty and students continues to grow and increase in importance. The group's wide range of industrial skills and experience along with our extensive network of real world practitioners provides invaluable resources to both faculty and students.

Merrimac Free Ferry, Merrimac, Wisconsin

The Merrimac Free Ferry caries Wisconsin SR 113 traffic across the Wisconsin River at Merrimac Wisconsin. The ferry has been in operation since 1960. Recent inspections uncovered fatigue cracks at several locations in the hull. The Infrastructure Technology Institute (ITI) of Northwestern University under contract to WisD0T installed a remote monitoring system on the boat to allow data to be gathered on the effects of live traffic and wind loading. The remote system utilizes three networked data conditioner/loggers and a local host computer. The data is transmitted by a wireless data link to a shore-based modem, which uses the local telephone line for outside communication. The system operates off of the ferry's power supply. Initial data gathered by the remote system showed that overload vehicles were the cause of the cracks in the ends of the hull but did not account for the growing cracks at the mid hull butt welds. One suspected cause of the mid-hull cracks is the excessive loading on the hull that results from ice pressure as the river freezes during the winter (Figure 15). To test this theory we modified the remote system for winter shutdown operation. Two temperature sensors (air and water) were added and provisions were made for heating the host computer compartment. Shore power was used to keep the system operational during the several months of winter shutdown.

Figure 15. Merrimac Ferry Icebound

The tests extended over four months from December 1999 through March 2000 during which time several freeze thaw cycles were observed. The data clearly showed very high strains are induced in the hull resulting from ice formation. These strains are the probable cause of the crack growth in the area of the fracture critical butt welds joining the hull halves.

WisDOT will use the test results in the development of a new ferry design. The new design will incorporate provisions for removing the boat from the water at the end of each season.

Michigan Street Bascule Lift Bridge, Sturgeon Bay, Wisconsin

ITI has been continuously remotely monitoring the Michigan Street Lift Bridge in Sturgeon Bay, Wisconsin, with strain gages and tiltmeters since 1995. Since the monitoring system was first installed, the structure has continued to deteriorate, monitoring technology has advanced, and concerns about the safety of the structure have grown. WisDOT and ITI engineers have decided that it is necessary to expand and update our current monitoring system. Additional sensors will be added to monitor the rack and drive train, motor currents, traffic weight in motion, and remote video. Professor Ed Rossow of Northwestern's Department of Civil Engineering visited the bridge this fall and provided assistance in selection of the new sensor configuration. The existing system was upgraded to modern standards and made wireless in Fall 2000. The remaining additions will be completed in spring/summer 2001. ITI student employees are currently working along with the freshman Engineering Design and Communication (EDC) program to integrate data collection from this bridge with the ITI web page and the ICCML.

Horse Creek, Stony Creek, and Hayfork Bridge, California

ITI currently has three remotely monitored bridges in California: Horse Creek, Stony Creek, and Hayfork. These are being monitored for structural stability and scour damage by means of tiltmeters and an onsite PC. Since the installation of the fist site in 1998, technology has advanced and the elements have taken their toll on the field equipment. It was decided that a maintenance trip was needed. ITI engineers and a summer student visited all three sites in November of 2000. The field PC at Horse Creek was replaced due to a hard disk failure, a tiltmeter panel damaged by corrosion was replaced at Hayfork, and all three sites received software upgrades. The trip also provided an opportunity for our student employee to field test a new Palm Pilot based tiltmeter interface he had programmed over the summer. This new interface would make on site checks by CalTRANS engineers easier by replacing their laptop computer with a Palm Pilot. All three California bridge monitoring sites are fully functional again.

Chesapeake City Bridge, Maryland

The Chesapeake City Bridge carries Maryland State Route 213 over the Chesapeake and Delaware Canal in Chesapeake, Maryland. It was constructed in 1948 and is owned by the U.S. Army Core of Engineers. The bridge has suffered from unusual fatigue cracking in the floorbeam connections since 1995. Michael Baker, Jr., Inc. has been hired to perform modeling and testing of the structure to determine the cause of these cracks. ITI has been asked to assist by testing all the bearings on the bridge for proper operation. Based on as-built bridge drawings supplied by the U.S. Army Core of Engineers, ITI engineers have designed and built a compact field testing unit based on LVDT measurement technology. Access to the bearings for testing by ITI should be in place in late February 2001.

Daniel Hoan Bridge, Milwaukee, Wisconsin

The Hoan Bridge is a tied arch bridge on I-794 in Milwaukee Wisconsin built in 1977. ITI researchers performed remote monitoring with strain gages and temperature sensors on the arch for WisDOT in 1996. In November, WisDOT invited ITI researchers to attend a planning meeting to deal with new cracks found in the approach spans. ITI was to instrument the bridge for a load test in the spring of 2001 in an effort to identify what was driving the crack growth. On December 13, one of the approach spans failed with cracks completely through two of its three girders. ITI engineers were present for the emergency planning sessions and the explosive demolition of the damaged span. As soon as weather permits, we will implement the original load test instrumentation plan as part of emergency inspections by Lichtenstein Consulting Engineers.

Indiana SR 62 Bridge over the Little Blue River, Sulphur, Indiana

A remote monitoring system was installed on one of the two main piers of the SR62 Bridge over the Little Blue River near Sulphur, Indiana (Figure 16). This pier had tilted during construction due to a partial slope failure. The problem was mitigated, however InDOT was still concerned over the long-term stability of the pier. ITI installed a remote monitoring system utilizing TDR and tilt sensors similar to the Klamath River Canyon bridge system previously installed in California. This effort is the first such program with InDOT. The system was installed early in December 1999 and is operating satisfactorily.

Figure 16. Remote Monitoring System Installation, SR62 Bridge over Little Blue River, Crawford County, Indiana

Kinnickinnic Avenue Bridge, Milwaukee, Wisconsin

The Kinnickinnic Avenue Bridge is a two-leaf simple bascule lift bridge built in 1996 in Milwaukee, Wisconsin (Figure 17). Since installation, Wisconsin engineers have observed higher than expected wear of the rack and pinion gears as well as higher than expected motor current during lift cycles. The Infrastructure Technology Institute of Northwestern University was asked to measure the pinion shaft torque before and after lubrication of the rack and pinion gears. On November 16th, 1999, ITI engineers installed four adhesive bonded strain gages to the pinion shaft along with a miniature data logger. Shaft torque was recorded as the bridge was opened and closed several times. ITI engineers immediately observed that the torque to open the bridge was almost the same as the torque to close the bridge. This clearly and immediately revealed the problem: The bridge was not properly balanced. A complete report with a test description, data, and pictures was submitted to the City of Milwaukee engineers on CD.

Figure 17. Kinnickinnic Lift Bridge, Milwaukee, Wisconsin

Warde School

The City of Chicago Department of Transportation undertook a major reconstruction and expansion of the Chicago Transit Authority Red Line subway station at Chicago Avenue and State Street in downtown Chicago. The underground station was lengthened in order to accommodate longer rush hour trains. The excavation for this expansion was to extend to within four feet of the F. X. Warde Catholic Middle School adjacent to Holy Name Cathedral. There was great concern over the possibility of damage to these nearby structures. Wiss, Janney, Elstner Associates (WJEA), Professor Richard Finno, and ITI performed various types of monitoring during the construction phase. ITI engineers placed a remote tiltmeter monitoring package with cellular telephone communication on the basement foundation wall in the school along with the WJEA instrumentation. The ITI tiltmeters were the same type used on our bridge monitoring projects. This project offered an opportunity to directly compare our instrumentation to another system as well as providing additional monitoring data for the project. ITI monitored the foundation from June 1999 through January 2000. The tiltmeters recorded acceptable small movements in the foundation and correlated well with the other instrumentation.

Compliant TDR Cable

During this report period the institute supported the research activities of several graduate students whose focus is Time Domain Reflectometry (TDR). ITI Research Engineer Dan Hogan has helped these students develop and fabricate special TDR cables that are very sensitive (Figure 18). The goal is to develop a compliant TDR cable that can be used to monitor slope stability in soft soils. Mr. Hogan uses his expertise in machining and prototyping to assist these students in the design, and construction of these special cables and the devices that are used to mechanically test them. The Institute has funded the installation and monitoring of these cables at several test sites in the Chicago area.

Figure 18. Compliant TDR Cable

Crack Monitor

The construction and mining industries are often accused of damaging homes and other structures near their operations due to the noise and vibrations resulting from their activities. Most nearby homeowners observe cracks in plaster walls or concrete foundations and conclude that construction vibrations caused them. Usually, however, the cause of these cracks is normal house settling or temperature and humidity changes unrelated to the construction activities. ITI staff has been assisting Professor Chuck Dowding with the development and commercialization of a remote crack and vibration monitor to address this problem since early 1999. The purpose of the crack and vibration monitor is to compare and quantify the growth rate of cracks due to construction, mining, or blasting activities to the growth rate due to normal changes in temperature and humidity. This is accomplished by sensors placed on cracks in a home, which measure the opening and closing of the crack. A description of the project and near real time data is available to the general public on the ITI web site:

http://iti.birl.northwestern.edu/acm/

ITI has assisted in the installation of two pilot systems in Evanston and one in Milwaukee Wisconsin (Figure 19). The Evanston sites were the Church Street Metra commuter rail station and a University owned wood frame building on Sheridan Road. The Milwaukee site is a private residence adjacent to an active mining operation.

Figure 19. Instrumented Home, Milwaukee, Wisconsin

Educational Activities

The institute staff continues to provide an increasing level of support to students and faculty. Two masters degree projects were completed during this period that involved considerable support effort from ITI staff.

Infrastructure Construction & Condition Monitoring Laboratory

ITI assisted the Civil Engineering department in creating an on-campus Infrastructure Construction & Condition Monitoring Laboratory (ICCML) to provide students with the ability to view activities at remote construction sites in real-time. The ICCML will be used to support classroom learning, student projects, career development, and student recruitment by bringing real-time images and data from field construction sites into the laboratory and classroom. The lab is located in the Technological Institute on the Evanston campus, and initially consists of a furnished workspace and two state of the art PC workstations with CAD and remote monitoring software. The lab was set up in December of 2000. ITI and Northwestern's Department of Civil Engineering are currently working to build partnerships with contractors for major construction projects. This will enable students to access live video, data, project management interactions, and engineering drawings from real sites through the ICCML. Integration of the lab with ITI's remote monitoring sites is ongoing.

Web-Zoomable Construction Monitoring Camera

In preparation for the above-described ICCML, ITI evaluated several remote video monitoring technologies. One stood out from the rest, Perceptual Robotics' web-zoomable remote camera, and was chosen for a "field test" on the roof of the 1801 Maple building. The extensive construction activities in the research park -- a new eighteen screen theater and commercial complex, 1460-car parking garage, hotel, research park building, and commercial office building -- provided an excellent opportunity to gage their camera's usefulness in monitoring live construction activities. ITI Engineers performed a complete installation on our own roof as part of the evaluation. ITI has purchased the test system and will transfer it to the next construction site monitored by the ICCML. The camera is currently located at:

http://live1.truelook.com/pri/icam?name=iti.itec.1

AISC/ASCE Steel Bridge Competition

Each year the Institute sponsors a group of civil engineering students who compete in the inter-collegiate AISC/ASCE Student Steel Bridge Competition. The students design, fabricate, and construct a steel bridge to be assembled during timed competition. Bridges are judged by weight, assembly time, deflection with a 2500# load and aesthetics. Participating students gain practical experience in structural design, fabrication processes, construction planning, testing, organization and teamwork. Dan Hogan serves as the staff advisor and supervises fabrication in the M.E. Prototype Shop. This year's team designed and fabricated a 22' long steel bridge that weighted 167 pounds (Figure 20).

The entire bridge consisted of 26 members and was assembled by a team of two men and four women in four minutes and fifteen seconds. The bridge was easily the best in the regional competition but unfortunately was disqualified from first place because of a minor technical violation. This was the third year for this activity at Northwestern and each year has seen steady improvement in the performance of the team and structure. Enthusiasm for the project continues to increase with undergraduate civil engineering students with the consensus being that the project provides a valuable experience in solving a difficult engineering problem as well as team building.

Figure 20. AISC/ASCE Northwestern University 2000 Contest Bridge

Outside Educational Activities

The Institute's Chief Research Engineer lectured at a two-day short course on Bridge Nondestructive Evaluation taught at the University of Wisconsin, Madison. The intensive two day short course covers advances in NDE for engineers and technicians in state and municipal transportation agencies as well as engineering consulting firms. Over 100 technical professionals attended the course from all over the U.S. and Canada. The course is taught in alternate years. Plans are under consideration to develop the course as a traveling seminar presenting it in various regions to alleviate the problems caused by lack of travel funds for public agency engineering staff.

Publications

“Continuous Remote Monitoring of the Merrimac Free Ferry,” David W. Prine and Darrell Socie, Presented at the Structural Materials Technology Conference, Atlantic City, NJ, February, 2000

Continuous Remote Monitoring of the Stony Creek Bridge,” Daniel Marron, Presented at the Structural Materials Technology Conference, Atlantic City, NJ, February 2000.

Ultra-sonic Technique for In-Situ Monitoring of the Setting, Hardening, and Strength Gain of Concrete

Principal Investigator: Prof. Surendra Shah

Summary

A new technique for the in-situ monitoring of the setting, hardening, and strength gain of Portland cement concrete was recently developed at the NSF Center for Advanced Cement Based Materials. The preliminary development of the technique was supported by the Federal Aviation Administration Center of Excellence for Pavement Research and the Infrastructure Technology Institute. The experimental procedure is based on ultrasonic measurements and consists of monitoring the wave reflection factor (WRF) at the interface between a steel plate and the hardening concrete. Preliminary studies have shown good correlation between the measured trends of WRF, the elastic modulus, and the hydration process of Portland cement concrete during the first 72 hours after placement.

The WRF technique has the potential to be a good tool for assessing early strength gain in concrete. The in-situ progression of the early hydration process can be monitored relatively easily using the WRF technique. A few potential applications of the technique are listed below.

- Cement and Admixture Industry: Conduct compatibility studies between Portland cement compositions and commercially available admixtures.

  Incompatible concrete mixture proportions and ambient conditions that lead to flash set during highway casting and paving operations can be easily identified using the WRF technique.

- Ready-mix Suppliers: 1) Identify material compositions and environmental conditions that could lead to early stiffening and flash set and 2) optimize paving and finishing operations for a given material composition.
- Precast and Concrete Industry: Determine optimum earliest time for de-molding/ removal of formwork
- Prestress Industry: Determine optimum time for application of prestress.
- State DOT's and Paving Contractors: Criteria for opening reconstructed and rehabilitated pavement to traffic can be developed.

This ultrasonic measurement is currently a laboratory tool, but an assessment of select industrial companies, including instrument manufacturers serving the concrete industry, indicated a strong demand for a “field friendly” device based on the WRF technique. The initial development showed promise for field application. Work in collaboration with Professor Mohsen at the University of Louisville, investigated three Kentucky DOT concrete compositions, and the rate of WRF attenuation was representative of the rate of strength gain. In order to develop field applications using this technique, robust field instrumentation and better data processing/ analyzing tools must be developed. Relationships between the WRF trends and the strength gain in concretes must also be developed in order to predict the ultimate strength of placed concrete under a range of temperatures and humidities.

Commercial Feasibility

A critical evaluation of the field applicability of the proposed technique and a feasibility study for further development of a field device for assessing the in-situ hardening and strength gain of concrete were conducted. The objectives of this feasibility study were:

- Identify industry demands and acceptance of the new field test.
- Determine the acceptable market price for a field device.
- Define the potential market for the field device at market price.
- Study the possibility of developing a standardized test method for in-situ monitoring of the hardening and setting of concrete, acceptable by agencies such as American Society for Testing Materials (ASTM).

  A literature review and an industry survey on the methods currently used in the field to determine the maturity of concrete and their shortcomings were performed. It was established that the "maturity method" is extensively used by industry in an attempt to estimate the in-situ gain of strength in concrete. Several shortcomings of the "maturity method" were identified through the literature review and are being addressed in the further development of the WRF technique.

- The ultrasonic techniques currently under development to characterize the properties of fresh cement paste were reviewed. A similar technique is being developed in Europe [Valic 1999]. Valic's results are similar to those obtained by the WRF technique.

  Promising applications of the WRF technique were identified based on the feedback from cement and admixture manufacturers, concrete suppliers, and precast component manufacturers. These have been listed in the summary. Feedback from NDE equipment manufacturers regarding the feasibility of developing and marketing a field device was also obtained.

- Several suggestions about improving the test technique to make it more robust and field applicable were made.
- The costs involved in producing a field device based on the WRF technique have also been identified and the market potential for such a device has been ascertained based on the past experience of the equipment manufacturers with similar devices.
- The collaboration of key instrument manufacturers for further development and marketing of a field device have been secured.

Technical Feasibility

Technical development of the WRF technique and associated hardware was conducted in the ACBM laboratories at Northwestern University. This work resulted in a laboratory demonstration of a "proof of concept" of the WRF technique to monitor the early-age setting and hardening of concrete. Subsequent collaborative work with Professor J. P. Mohsen, at the University of Louisville, tested the WRF technique on large slabs of concrete, using three different concrete compositions currently employed by the Kentucky DOT in highway and bridge construction. The results were very encouraging, in that the rate of WRF attenuation reflected the rate of strength gain in the setting and hardening concrete. The test setup and graphical relationships are shown in Figures 21 and 22. Concrete industry feedback, gathered during the feasibility study, indicated that the WRF technique must be able to predict the ultimate strength of placed concrete under a variety of temperature and humidity conditions. The next phase of technical development will address the measurement of a variety of concrete compositions, under varying conditions, as well as a large-scale evaluation of the WRF technique.

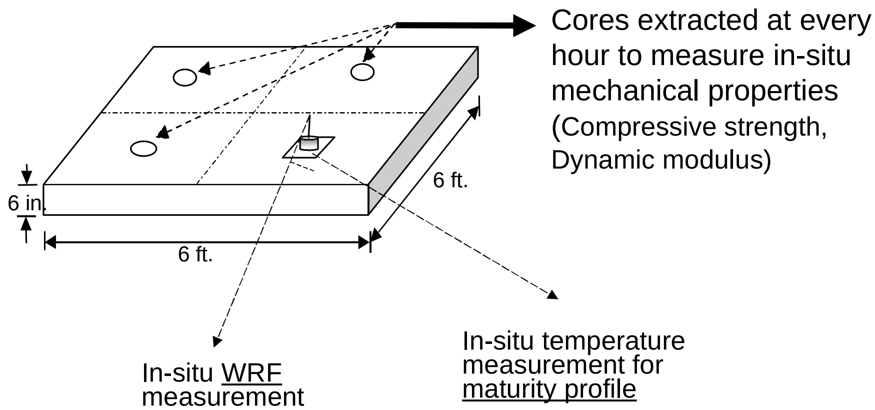

Figure 21. Evaluation of the WRF Technique -- University of Louisville

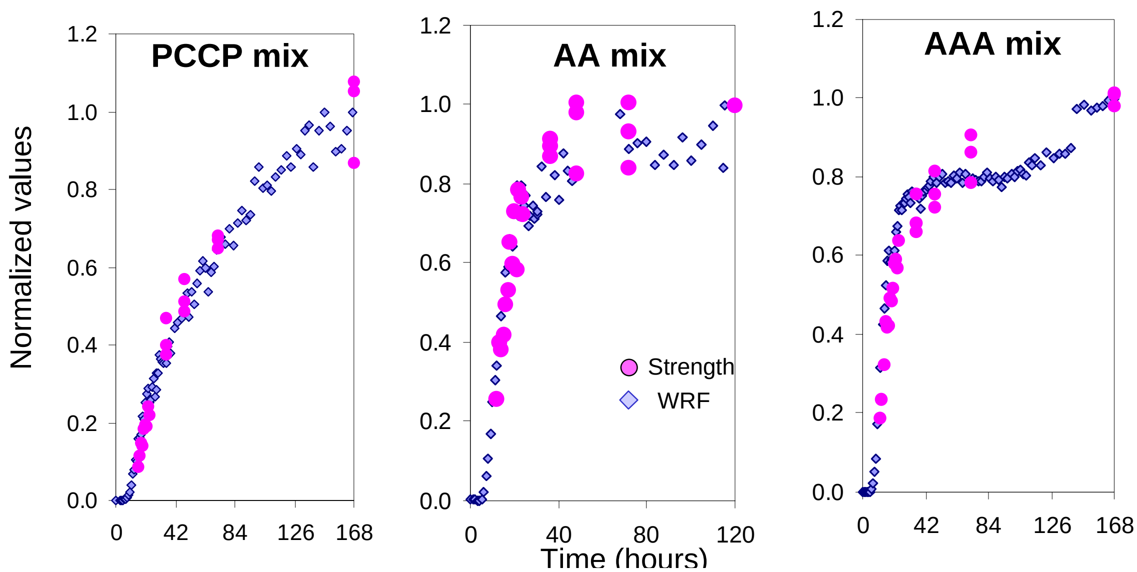

Figure 22. Comparison of Normalized WRF and Strength Gail for Three Kentucky DOT Compositions: PCCP (Normal Strength), AA (Bridge Mix), and AAA (High Early Strength)

Dissemination of Technology

The WRF technique has been discussed in a variety of venues. Papers, presentations, and other technology transfer actions include:

- Subramaniam, K. V., and Shah, S. P., “Determining Early Stiffening and Strength Gain by Non-Destructive Techniques for Early Serviceability of Structures”, ACBM Semi-Annual Program Review Meeting, November 2000, Springfield, Illinois.

- A four-page, ACBM summary featuring the WRF technique was prepared and distributed at the CERF (Civil Engineering Research Foundation) Symposium 2000, recently held in Washington, D.C.; and the Strategic Development Council of the American Concrete Institute, which met in Atlanta in November 2000. This handout will be used at subsequent technical meetings to promote this work.

- The WRF development work was the feature article in ACBM’s fall edition of *Cementing the Future*, a newsletter that is distributed to over 4000 industrial and academic personnel in the cement and concrete industries.

- Professor J. P. Mohsen will present a paper on the WRF technique at the January 2001 meeting of the TRB (Transportation Research Board) in Washington, D.C.

- RILEM (Réunion Internationale des Laboratoires d'Essais et de recherche sur les Matériaux et les Constructions) has started a new committee: “Early Age NDE of Concrete”. Professor Shah serves as a member of that committee.

Personnel

The primary work on the development of the WRF technique has been conducted by post-doctoral fellow K. V. Subramaniam, now an Assistant Professor at New York College, and by post-doctoral fellow Y. Akkaya. Professor J. P. Mohsen at the University of Louisville has carried out collaborative work.