

Title: **Condition Assessment of Buried Metal-Tensioned Elements**

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Condition Assessment of Buried Metal-Tensioned Elements

by

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ABSTRACT

This paper describes application of nondestructive test (NDT) methods for condition assessment of metal-tensioned elements in geotechnical engineering applications including rock bolts, ground anchors and soil nails. Electrochemical tests, such as measurements of half-cell potential and polarization, are used to detect the presence of corrosion and evaluate the integrity of corrosion protection systems. Mechanical wave propagation techniques, such as impact and ultrasonic tests, are used to locate features along the length of an element including loss of cross section from corrosion. Interpretation of test results requires knowledge of the electrical continuity between elements being tested, and knowledge of the details associated with the installation of the system being evaluated.

The utility of the NDT's are evaluated under controlled conditions on bench scale specimens in the laboratory, and on buried specimens at a specially developed insitu test facility. However, given the numerous variables inherent to field installations that may have an effect on the measurements, it is necessary to study performance of the NDT technologies in the field.

Results from condition assessment employing NDT technologies of tie-backs for a quay wall in Buffalo, New York, and of rock bolts along a highway cut in Dresden, New York are described. Background information is given for each site including a description of the aggressiveness of the environment relative to corrosion in terms of results from chemical analysis of native soil samples.

Results from NDT correlated well with features of the tieback and rock bolt installations. Electrochemical test results indicated that corrosion was occurring, but the wave propagation tests did not indicate any significant loss of cross section. NDT measurements should be archived to serve as a baseline against which future NDT results may be compared.

INTRODUCTION

Buried metal-tensioned systems include prestressed ground anchors (strands and bars), soil nails, and rock bolts. These systems have been used with increasing frequency by transportation agencies for the construction and repair of foundations, retaining walls and excavated and natural soil and rock slopes. Although soil nailing is a more recent innovation, rock bolts were first used in the mining industry, and later adopted for use by the transportation industry in the early 1960's. The use of permanent ground anchors for public sector projects became common in the United States in the late 1970's.

Thus, some of the earlier rock bolt and ground anchor installations are approaching a service life of approximately 30 to 40 years. Since visual observation of conditions at the element head assembly is often not indicative of potential problems, the condition of existing systems is uncertain. Transportation agencies, faced with the task of allocating budgets to rehabilitate aging facilities, need a protocol for performing condition assessment and estimating the remaining useful service life. This paper presents results from an on-going study to develop procedures to evaluate the condition and remaining useful service life of in-place, buried, metal-tensioned systems.

This paper describes application of several nondestructive tests (NDT's) to monitoring and condition assessment of buried metal-tensioned systems. Electrochemical tests, such as half-cell and polarization measurements, are used to explore the nature of the corrosion process. Mechanical tests including impact and ultrasonic tests, based on the principal that the vibration characteristics of the element are affected by features encountered by waves traveling along its length, are used to distinguish locations of distress along the element.

Preliminary evaluations of NDT include bench-scale laboratory tests, and tests performed on elements with known features buried in a test bed. Brief details of the preliminary evaluation are presented, and these serve to demonstrate calibration of the instruments, the potential for application of the test method, and the sensitivity of measurement. However, given the numerous variables inherent to field installations that could affect the measurements, the performance of the NDT technologies need to be studied in the field.

Evaluations of anchors supporting an anchored quay wall in Buffalo, NY and of rock bolts supporting a rock cut in Dresden, NY are presented. Subsurface conditions at each site are described, and results from measurement of soil pH, soil resistivity, sulfate and chloride ion concentrations are provided, followed by results from NDT. Visual inspections of anchor elements at the Buffalo site are used to confirm results from NDT.

DESCRIPTION OF NDT

Electrochemical tests including measurement of the half-cell potential and polarization are used to assess if corrosion is present, and element surface area vulnerable to corrosion. Results from these tests may indicate that corrosion is occurring or can occur, but mechanical tests are needed to determine whether the condition of the element has been compromised by

loss of cross section. Wave propagation techniques, such as impact and ultrasonic tests, are used to assess the existing condition of elements (i.e., severity of corrosion).

While most of the equipment considered for NDT can be obtained commercially, its specific application to buried metal-tensioned elements is the subject of this paper. Quality control and margins of error for test measurements are beyond the scope of this paper.

Half-Cell Potential

The half-cell potential is the difference in potential between the metal element and a reference electrode as shown in Figure 1. A copper/copper sulfate reference electrode (CSE) is used in this study. For a given material in a given environment, the potential is an indicator of corrosion activity. Interpretation of the data needs to consider whether the element being tested is electrically isolated.

In general, as element corrosion becomes greater, the half-cell potential becomes increasingly positive. This trend is useful if the element is electrically isolated. The possibility that relatively greater corrosion has occurred along the surface of an element may be identified if its half-cell potential is more positive relative to the potentials observed for other elements at the same site. As a guide, the half-cell potential (with respect to CSE) of clean, shiny, low carbon steel in neutral soils and water ranges from -500 mV to -800 mV; and the half-cell potential of rusted, low carbon steel in neutral soils and water is between -200mV and -500mV. Although the test results may be useful to identify where corrosion has occurred, it does not mean that the corrosion process is still taking place.

More negative half-cell potentials indicate a greater potential for corrosion at that element. This trend is useful if electrical connectivity exists between elements. Here, the element with more positive half-cell potential acts as cathode and the element with the lower half-cell is the anode, where corrosion can occur. As a guide, considering reinforcing steel bars embedded in concrete, limits recommended by ASTM C876 suggest that half-cell potentials more positive than -200 mV indicate a low likelihood that corrosion is occurring, while values more negative than -300 mV indicate a high likelihood that corrosion is occurring. Although the potential for corrosion may be indicated by this condition, it does not necessarily mean that corrosion has occurred.

Polarization Measurements

The method, shown in Figure 2, involves installing a common ground at some distance from the measurement location, applying a known voltage between the metal element and the ground bed and observing the relationship between surface potential and impressed current (E vs. log I). Impressed current flows through the soil/water electrolyte from the element to the ground bed. Negatively charged ions within the soil/water electrolyte migrate towards the positively charged element. Current is increased in increments and the change in potential of the element surface is observed. The basic premise of the test is that a level of current is reached for which the surface of the element is polarized and saturated with negatively charged ions. For the test data to be meaningful, the tested elements must be electrically isolated from the remainder of the system.

Polarization measurements may be correlated with surface area of bare metal in contact with the ground. Data from the E vs. $\log I$ relationship is plotted and the shape of the resulting curve is evaluated. The characteristic plot has an initial straight-line section curving into a second straight-line section (at a different slope) as shown in Figure 3. The second straight-line portion of the curve is known as the Tafel slope, and the first point on the tangent to this slope gives the polarization current.

According to unpublished data compiled by the pipeline industry for bare metal in contact with soil, approximately 21 milliamperes (mA) is required to polarize each square meter of surface area. Using this constant, the surface area of steel in contact with the ground can be computed using the measured I_p . The estimated current requirement, I_{theory} , can be compared to measured current requirement, I_p , with three possible outcomes:

1. If $I_p \ll I_{\text{theory}}$, the element is probably electrically well insulated, and well protected.
2. If $I_p < I_{\text{theory}}$, the element is probably coated or protected over just some part of its surface. Using the measured protection current (I_p), the unprotected length of the element can be estimated.
3. If $I_p > I_{\text{theory}}$, this suggests that more surface area is involved than initially assumed, and could be an indicator that electrical contacts with other elements having surface areas in contact with the ground have not been considered.

This information can be used to assess the integrity of existing corrosion protection systems, which may involve plastic sheathing, or other dielectric material surrounding, or coating the element.

Impact Test

The impact test, shown in Figure 4, may be used to evaluate cracking of grouts, fracture of tendons and loss of element section. The specimen is impacted using a hammer or ball device, which generates elastic compression waves with relatively low frequency content. The traveling waves are reflected whenever a change in material or geometry is encountered along the length of the element. Equipment required for the impact echo test method includes an impact device, an accelerometer, velocity or displacement transducer for measuring the specimen response, and a data acquisition system. The signal is processed with a signal conditioner that also includes a power supply with necessary excitation. As shown in Figure 4, tests may be conducted with the impact and receiver placed at the same end of the bar.

The impact test procedure involves, (1) striking the bar with the impact device to generate compression waves along the specimen, and (2) detecting reflected waveforms with an accelerometer attached to one end of the bar. Test results are processed in both time and frequency domains.

Ultrasonic Test

The ultrasonic test method is another technique for evaluating grout condition, fracture of elements, and abrupt changes in the element cross-section. The method has many of the features of the impact echo technique, except that the transmitted signal contains relatively higher frequencies. Ultrasonic waves are radiated when an ultrasonic transducer applies periodic strains on the surface of the test object that propagate as stress waves.

With the pulse-echo method (single-probe operation) shown in Figure 5, the time taken for sound pulses, generated at regular intervals, to pass through the specimen and return, is measured. The transducer, which is acoustically coupled to the exposed end of the element, receives a shock excitation, and generates a short ultrasonic pulse. The transducer receives echoes of the pulses after reflection. The return of the leading edge of the first echo can be easily detected by visual means from the time-history of transducer output.

PRELIMINARY EVALUATION OF NDT

To evaluate the viability of candidate NDT test methods, a series of tests were conducted using bench-scale, and in-situ test facilities. The tests allowed the NDT methods to be evaluated under controlled conditions. Initially, bench-scale tests were performed such that measurements from wave propagation tests, including impact and ultrasonic tests, could be compared to results from analysis of one-dimensional wave propagation along a cylindrical rod. NDT methods were further evaluated using in-situ test specimens, which were buried and surrounded by soil similar to field installations.

Bench Scale Test

Tests were conducted using mechanically isolated, 2-m long, 32-mm diameter, Dywidag bars having free boundary conditions at each end. The observed dynamic response was compared to that predicted with equations based on one-dimensional wave propagation along a slender bar:

$$f_n = \frac{nV_c}{2L} \quad (1)$$

where,

f_n = natural frequency of vibration

n = an integer

V_c = compression wave velocity \approx 5500m/s for steel

L = length

Based on Eq. 1, the first three natural frequencies of an approximately 2 m long bar are 1.4, 2.8 and 4.2 kHz. Test results presented in Figure 6 are in agreement with the predicted response. Figure 6 also shows results from testing a similar bar with a notch, cut approximately mid-length along the bar. Compared to the results obtained for the intact bar, an additional reflection from the defect is evident in the results.

The same specimens used for impact echo testing were also used to evaluate the ultrasonic test technique. The response of the mechanically isolated bar with no defect is shown

in Figure 7. Reflections are observed at intervals of approximately 0.73 ms, which correlate well with the length of the bar ($t = 2L/V_c = 2(2)/5500 = .727$ ms).

In-Situ Test Facility

The in-situ test facility at the State University of New York at Buffalo is shown schematically in Figure 8. Eight, 3-m long elements were installed vertically in 150-mm diameter, 2.75-m deep, auger holes. Specimens were placed along two rows, and separated by approximately 4.5 m. All of the elements have a 0.3 m long grout bulb at their lower end, to simulate anchorage of the bars and tendons in soil. The grout bulbs were precast at the bottom end of the specimens prior to installation.

Four types of elements were installed at the U.B. Test Facility including:

- 1) 32 mm diameter plain Dywidag bars
- 2) 32 mm diameter epoxy coated Dywidag bars
- 3) 32 mm diameter plain Dywidag bars surrounded by grout encased in a 2.7m long, 10 mm diameter plastic pipe
- 4) Polystrand 15-mm diameter, seven-wire strand coated with grease, and surrounded by an extruded HDPE sheath

Two specimens were installed for each element type: one intact without any defect, and the other with a defect. Defects were constructed as a notch placed about 1 m from the far end of the bar. The notch removed approximately 25 percent of the bar cross-section over a length of 75 mm. For grouted specimens the notch extended through the grout and into the bar. For strand elements, the defect was created by stripping a 75 mm length of the HDPE sheath and exposing the strand to the subsurface environment.

Soil at the site is fine grained with varying amounts of gravel and is classified as CL according to the Unified Soil Classification System (USCS). Measured moisture contents range from 8 to 13.5 percent, most likely corresponding to the moisture content during compaction of the fill, and a degree of saturation between 60 and 90 percent.

Electrochemical testing included half-cell potentials and observation of the E vs. log I relationship. The ground bed utilized for the polarization test consisted of three, 1 m long, copper plated rods, located approximately 30 m south of Element 1. The half-cell was located on the ground surface within approximately 0.3 m of each element during testing. Table 1 summarizes results from the electrochemical tests.

Compared to the typical potential of -200mV to -500 mV (CSE) normally observed for rusted low carbon steel in neutral soils and water, the corrosion potentials shown in Table 2 indicate that corrosion had occurred in Specimens 5 and 8. The lengths of exposed element (L_e), estimated from polarization test results, are consistent with the known conditions of the elements. Element 1 was in direct contact with the ground for the majority of its length. By contrast, Element 5 was insulated with grease and plastic sheathing. This is reflected in the relatively large and small values of L_e for Elements 1 and 5. Elements 4 and 6 had L_e roughly

corresponding to the 75-mm long defect. The larger L_e of Bar 8 includes some exposed metal near the top of the element in contact with the ground.

NDT OF EXISTING INSTALLATIONS

Buffalo Inner Harbor

In 1967, a 12-m high, sheet-pile quay wall was constructed at the future site of the Buffalo Inner Harbor Development Project. The wall was supported with a single row of anchors located approximately 1.0 m below the top of the wall. Wall anchors were smooth bar elements threaded at each end (upset rods), made from mild steel with a diameter of 64 mm at the upset end and 51 mm along the shaft. The bars were anchored to a sheet pile deadman located approximately 17 m behind the wall face. Double channel walers were attached to the inside of the wallface and along the backside of the sheetpile deadman. Bars were attached to the walers with nuts and bearing plates at each end. Approximately 8.5 m long bar lengths were coupled to span between the wall face and the anchor sheets. A corrosion protection system was not included in the design of the anchors.

In support of the development, a site investigation was performed. Test borings were advanced behind the existing quay wall, and soil samples were retrieved for laboratory testing. Bedrock elevations correspond to the toe of the wall at a depth of approximately 12 m from the ground surface. Soil deposits on top of the bedrock include approximately 9 m of natural soil deposits followed by 3 m of granular fill. The mean lake elevation, and corresponding groundwater level, is approximately 3 m below the ground surface (and the top of the wall). Based on this information and observations of the elements made during NDT at the site, the wall anchor elements are located within the fill and completely above the ground water table.

Laboratory testing conducted on the granular fill includes moisture content, grain size analysis, and chemical analysis including pH, and measurement of trace compounds typical of those conducted for environmental assessment. The pH measured on two samples of the fill was 7.0 and 6.38 and the presence of sulfides was not detected (< 11 mg/kg).

In summary, the fill is relatively free draining, and is classified as poorly graded gravel, GP, by the USCS. Although the soil resistivity was not measured directly, for a free draining gravel material, with neutral pH, the resistivity is estimated to be above 5000 ohm-cm. Based on this information, and since the wall anchor elements were located above the water level, site hazard is considered low.

During spring and summer of 2000, the quay wall was demolished and replaced with a new quay wall constructed approximately 15 m behind the location of the original wall. During construction of the new quay wall, backfill behind the old wall was excavated and the anchor bars were exhumed. The coupling was unearthened and its location, approximately 8.5 m from the end of the bar, documented. Figure 9 shows the quay wall, backfill, and unearthened anchor behind the wall, along with the condition of the anchor elements and the anchor coupling.

Visual observation of the exposed bars indicated that they were in very good condition with a relatively uniform coating of rust surrounding the bars. Significant loss of cross section, or

surface pitting was not observed. Access to the end of the anchors was available from the excavation on the backside of the sheetpile deadman.

NDT was performed on three elements at the site, located next to one another, at a spacing of approximately 2 m. Bar 1 was located in the middle, and Bars 2 and 3 were located approximately 2 m east and west of Bar 1, respectively.

Time-histories from impact testing performed on Bars 1, 2 and 3 are compared in Figure 10. A reflection at 3.1 mS is evident in the test results from Bars 1 and 3, and although present for Bar 2, it is less discernible. The reflection at 3.1 ms is consistent with the observed location of a mechanical coupling about 8.5 m from the end of the bar ($8.5 \text{ m} \times 2 \div 5500 \text{ m/s} = 0.0031 \text{ s}$).

NYS Route 22, Dresden Station, NY

This site is located along New York State (NYS) Route 22 near Mile Post 1642, in Dresden, which is north of Whitehall, NY. The highway cut is made within a gneiss rock formation that has a major joint set dipping obliquely to the alignment of the highway. The joints are spaced at approximately 3 m to 6 m intervals and have an aperture of approximately 50 mm that is infilled with fine sand.

Fifteen, 32-mm diameter, 6 m long, resin-grouted rock bolts were installed at this location in 1990. The bolts are installed at the base of a near vertical cut as shown schematically in Figure 11. A lower rock joint is exposed near the base of the cut, which served as a bench for accessing the bolt heads with climbing ropes and a ladder. The site was of particular interest because four of the bolts were instrumented with load cells. NYSDOT has monitored the load cells, on a quarterly basis, since the installation of the load cells. Three of the bolts were prestressed to 220 MN and one bolt was prestressed to 440 MN. Generally, measured loads remained stable, exhibiting only minor fluctuations over the monitoring period.

Samples of infilling and rock were collected by hand during the site visit. Table 2 summarizes the laboratory testing performed on the samples. Based on this information, the infilling is classified as well graded sand with silt (SW-SM). Chemical testing of the infill indicated that the pH was close to neutral and the resistance was relatively high such that high rates of corrosion were not expected. Furthermore, resin grout surrounding the rock bolts tended to isolate elements from the surrounding rock mass. However, because resin grout may not completely surround the elements, some of the bolt lengths may have been exposed. NDT was used to assess the condition of the resin grout, and to determine if there had been any significant loss of loss section.

Six rock bolts were evaluated by NDT at the site. Each of the instrumented bolts was tested, referred to as Bolts 1, 2, 3 and 4. Bolts 1 and 2 are located at the south end of the site, and Bolts 3 and 4 are located 40 m away at the north end. Bolts 5 and 6 (not instrumented) are located near Bolts 1 and 2.

Based on continuity checks, the bolts appeared to be electrically isolated from one another. Half-cell measurements from Bolts 1, 2, 5 and 6 ranged from -555 mV to -633 mV. Half-cell measurements from Bolts 3 and 4 were more positive, -144 mV and -200 mV,

respectively. The more positive readings for Bolts 3 and 4 indicate that corrosion may have occurred at some point along their length; most likely close to the rock face.

Polarization measurements of Bolts 5 and 6 rendered $I_p \approx 1$ mA indicating that approximately 0.48 m ($L \approx 1.0$ mA/2.1 mA/m) of these elements were not electrically insulated by resin grout and were in contact with the surrounding rock or joint infilling material. Results from impact and ultrasonic testing indicated that this was likely due to the drill hole not being completely filled with resin grout.

Figure 12 shows the frequency response, for Bolt 1, which is typical for all four of the bars evaluated by impact testing. The figure shows that five or six predominant frequencies can be correlated with physical features of the rock bolt installation. Five main features of the installation include the end of the bolt, seam location, grout column, and plates located at each end of the load cell. These locations are identified in Figure 11 by the distance from the end of the bar designated as L_1 to L_5 . Table 3 presents the estimated lengths to these physical features based on the observed fundamental frequencies and application of Eq. 1.

Reflections were evident in the ultrasonic test results corresponding to L_3 , L_4 , and L_5 . Reflections from more distant features including L_2 and L_3 are difficult to detect in the ultrasonic test results because the amplitudes of the reflections are very small and may be masked by the larger amplitude reflections from features closer to the face of the rock bolts.

The measured loads in Bolts 1 to 4, appear stable indicating that the elements are not currently distressed. At the time of the NDT evaluation, the bars had been in service for 10 years and given the environment (i.e., pH, resistivity, sulfate and chloride content), this is not enough time for the elements to have undergone significant corrosion. Results from electrochemical tests indicate that corrosion may be occurring, but results from wave propagation tests do not reveal any significant loss of cross section. However, the impact and ultrasonic test results correlate well with physical features of the installation including the observation of a gap between the backside of the anchor plate and the grout column. Future monitoring of these elements is recommended since they are vulnerable to corrosion near the anchor head. These NDT results can be useful as baseline measurements to which future NDT results can be compared.

CONCLUSIONS

The paper describes application of several NDTs for condition assessment of buried metal-tensioned systems such as ground anchors, rock bolts and soil nails. Electrochemical tests including half-cell potential and polarization measurements are useful for indicating whether corrosion is present and for assessing the integrity of existing corrosion protection systems. However, these tests are not useful for assessing the severity of corrosion, or locating where corrosion has occurred along the length of an element.

Impact and ultrasonic tests can be used to locate significant loss of cross section. Interpretation of results from impact or ultrasonic tests requires knowledge of installation details. Ultrasonic tests may detect features within approximately 1 m from the element face; however, reflections from more distant features are often obscured.

Preliminary evaluations of NDT were performed under controlled conditions using bench scale, and insitu specimens. Preliminary evaluations demonstrate that a condition assessment protocol using NDTs can provide useful information about the integrity of existing corrosion protection systems and loss of element cross section. The consistency observed between impact and ultrasonic test results serves to verify the calibration of different equipment used to make the measurements.

Condition assessment, including application of NDTs, was demonstrated at two field sites with existing installations of metal-tensioned systems. Anchor elements at the Buffalo Inner Harbor project were unearthed. Impact test results correctly identified known features of the installation, including a coupling located approximately 10 meters from the end of the anchor. Data from the Buffalo Inner Harbor site demonstrate that the impact test technique may be successfully applied to elements up to 10 meters long.

According to results from electrochemical tests performed on rockbolts in Dresden, NY, resin grout does not completely cover the bolts over their entire length, and corrosion is occurring in some bolts. Impact test results indicate that significant loss of element cross section has not occurred. This conclusion is supported by the fact the test results clearly display features associated with the far end of the 6 meters long bolts. If significant loss of cross section were present, effects from the far end of the element would be obscured in the test results. Therefore, at the time of testing, corrosion does not appear to have significantly affected the condition of elements. This site is a good candidate for continued monitoring and condition assessment to document the condition of the elements over time.

NDT results are qualitative in the sense that data from each element at a site can be compared to one another, and to results expected based on known details of the installation. Elements should first be screened using the electrochemical tests to determine locations where corrosion is likely to occur. The results from electrochemical tests can be supplemented with results from the impact response and/or ultrasonic tests to identify and locate defects along the length of the element. Subsequent confirmation of element condition from invasive observation and/or lift-off tests should be recommended.

ACKNOWLEDGEMENTS

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TABLE 1 Summary of Electrochemical Test Results (11/22/99) from UB Test-bed Specimens

Element #	Description	E_{corr} (mV)	I_p (mA)	A_s (m ²)	L_e (mm)
1	Plain bar (d = 32 mm)	-620	6.0	0.2860	2857
4	Epoxy bar w/defect (d=32 mm)	-752	0.2	0.0095	95
5	Strand (d = 15 mm)	-263	≈ 0	≈ 0	≈ 0
6	Strand w/defect (d = 15 mm)	-678	0.1	0.0048	101
8	Grouted bar w/defect (d = 32 mm)	-308	0.8	0.0380	379

E_{corr} is the free corrosion potential with reference to the half-cell

I_p is the polarization current observed from the E vs. Log I relationship

$A_s = I_p/21$ is the estimated surface area of the element in contact with the ground

$L_e = A_s/\pi d$ is the length of the element corresponding to A_s , and d is the element diameter.

TABLE 2 Summary of Rock Infill Properties from Rock Cut along NYS Route 22 in Dresden, NY

Sieve Size (U.S. Standard)	% Passing
19 mm	100
#4	94
#40	51
#200	8
D ₆₀ = 0.6 mm	
D ₃₀ = 0.3 mm	C _c = 1.2
D ₁₀ = 0.1 mm	C _u = 6.2
Atterberg Limits	
Liquid Limit	N.A.
Plastic Limit	N.A.
Plasticity Index	N.A.
Chemical Analysis	
Measured Moisture Content (w%)	16.1
Resistivity (ohm-cm)	5900 (min. at w = 23.6%)
pH	6.9
Sulfate Content (mg/kg)	4.3
Chloride Content (mg/kg)	< 10

TABLE 3 Summary of Impact Tests on Rock Bolts at Dresden Site

Range of Predominant Frequency (Hz)	Description of Physical Feature Correlated to Range of Predominant Frequency	Computed Length from Face ¹ of Rock Bolt to Physical Feature as Shown in Figure 11
450 - 500	End of rock bolt	L ₁ - 5.5 m to 6.1 m
1,000 – 1,500	Seam location	L ₂ - 1.83 m to 2.75 m
5,000-6,000	Beginning of grout column	L ₃ - 0.46 m to 0.55 m
7000 – 10,500	Nut and plate at bottom of load cell	L ₄ - 0.26 m to 0.39 m
11,500 – 16,000	Nut and plate at top of load cell	L ₅ - 0.17 m to 0.24 m

¹ Accelerometer mounted to the exposed face of rock bolt

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FIGURE 1 Half-cell potential measurement

FIGURE 2 Test arrangement for measuring polarization current

FIGURE 3 Typical result from polarization measurement

FIGURE 4 Schematic of Impact Echo Test

FIGURE 5 Schematic of Ultrasonic Test

FIGURE 6 Time and frequency-domain response for impact test on 2.0m long intact bar and bar with defect (25% section reduction and 75mm long notch in the middle)

FIGURE 7 Ultrasonic test results for bench-scale 2 m long plain bar without defect

FIGURE 8 Plan view of in-situ specimens

FIGURE 9 Thirty-three Year Old Bars, Backfilled in Free Draining Gravel Behind the Old Quay Wall, and Unearthed at the Buffalo Inner Harbor Project

FIGURE 10 Comparison of Time-Histories from Impact Tests Performed on Bars Nos. 1-3 at Buffalo Inner Harbor

FIGURE 11 Schematic of Rock Bolt at Dresden, NY

FIGURE 12 Typical frequency response from Impact Tests on rock bolts at Dresden, NY

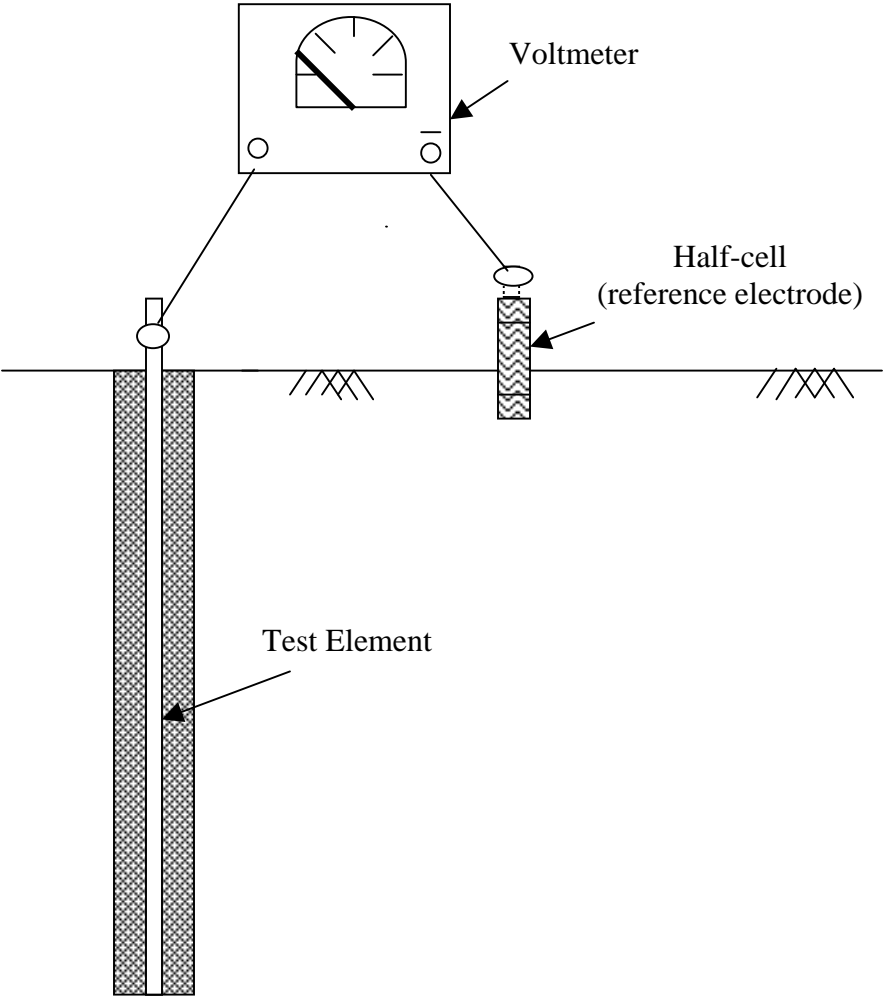


FIGURE 1 Half-cell potential measurement

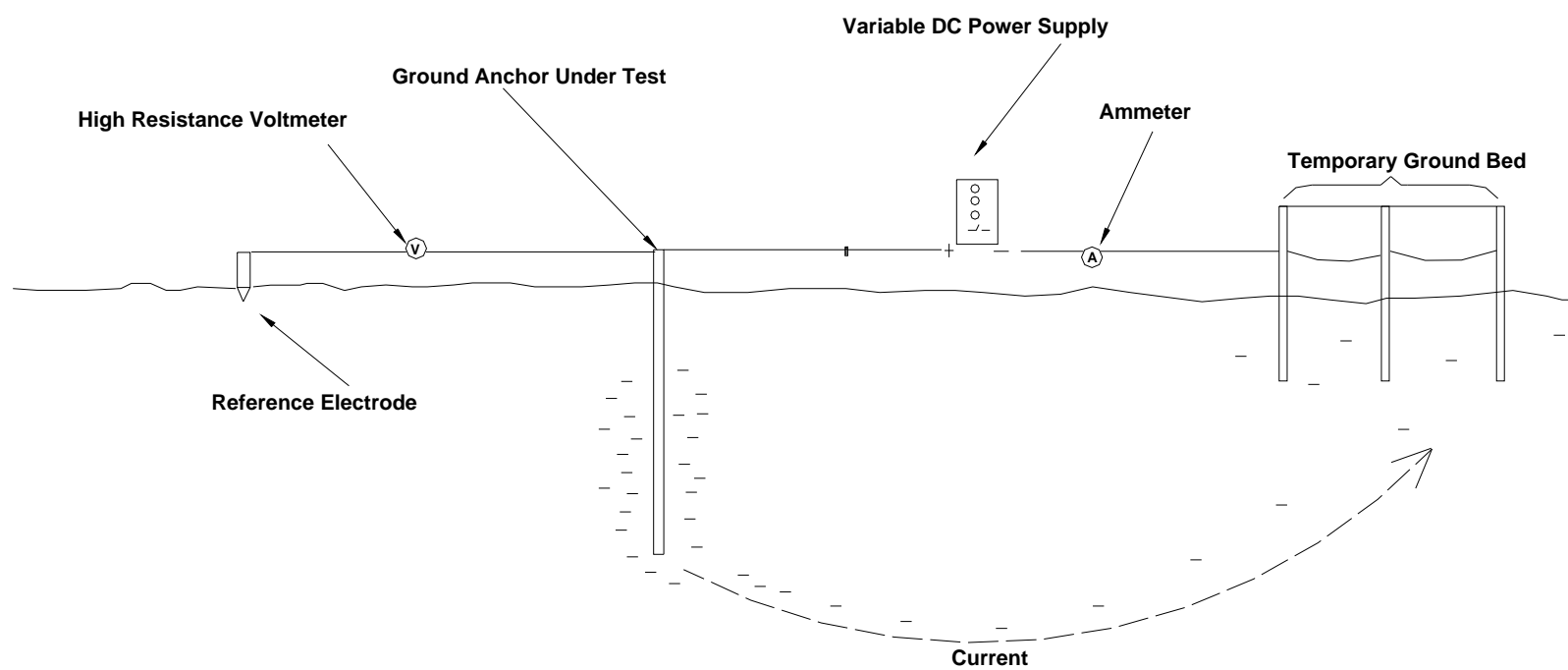


FIGURE 2 Test arrangement for measuring polarization current

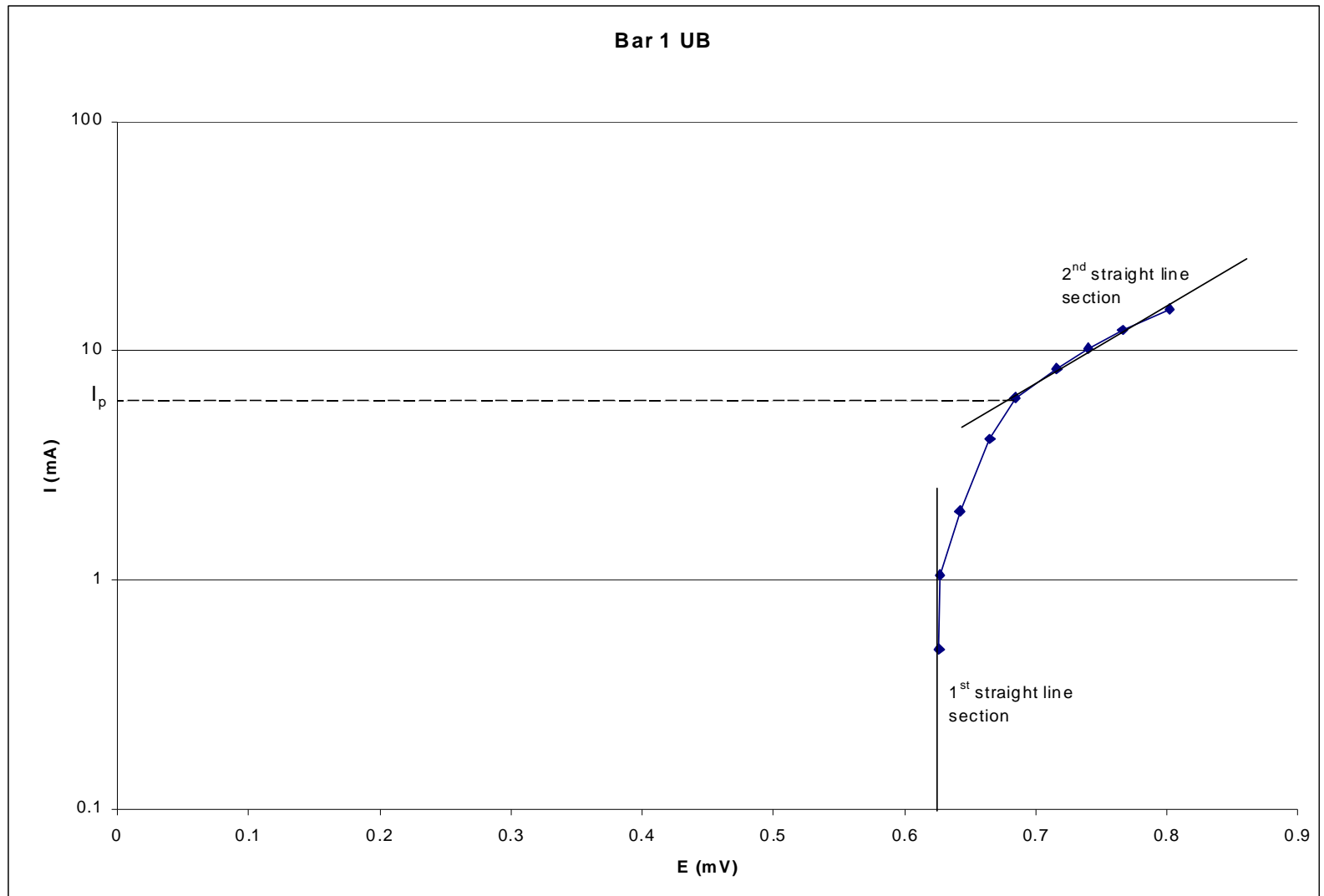


FIGURE 3 Typical result from polarization measurement

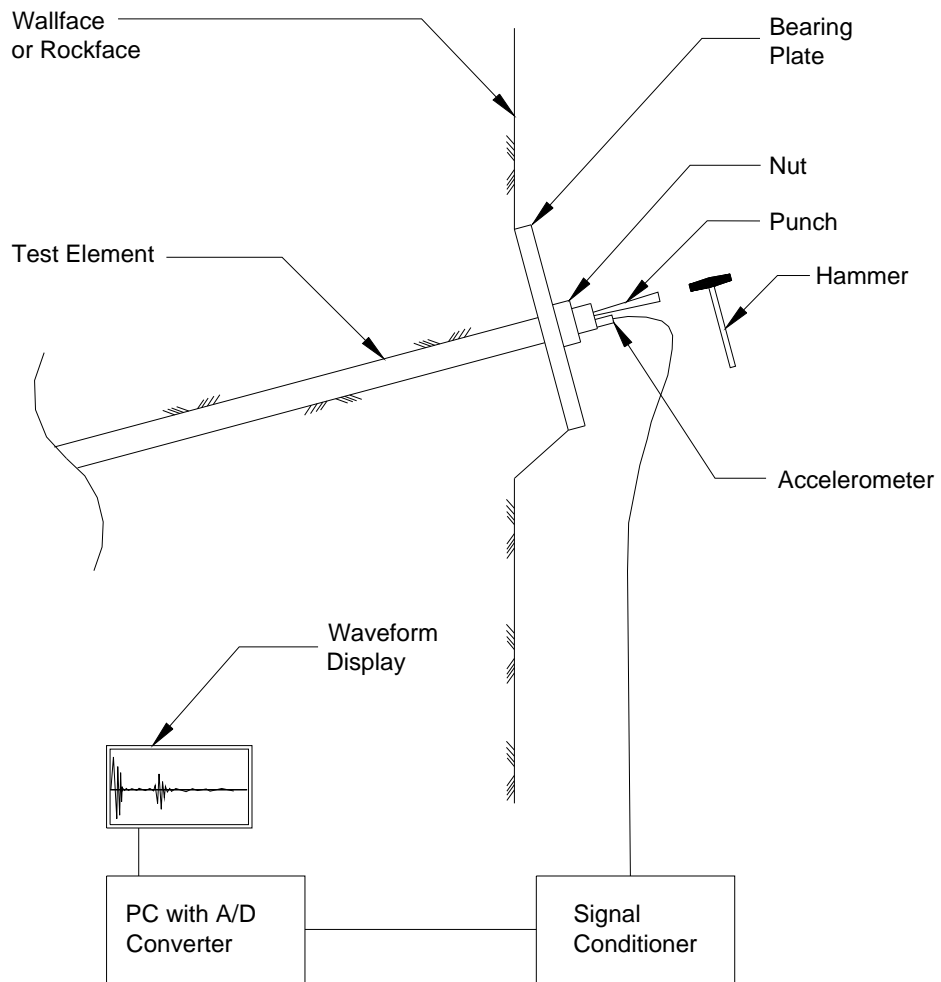


FIGURE 4 Schematic of Impact Echo Test

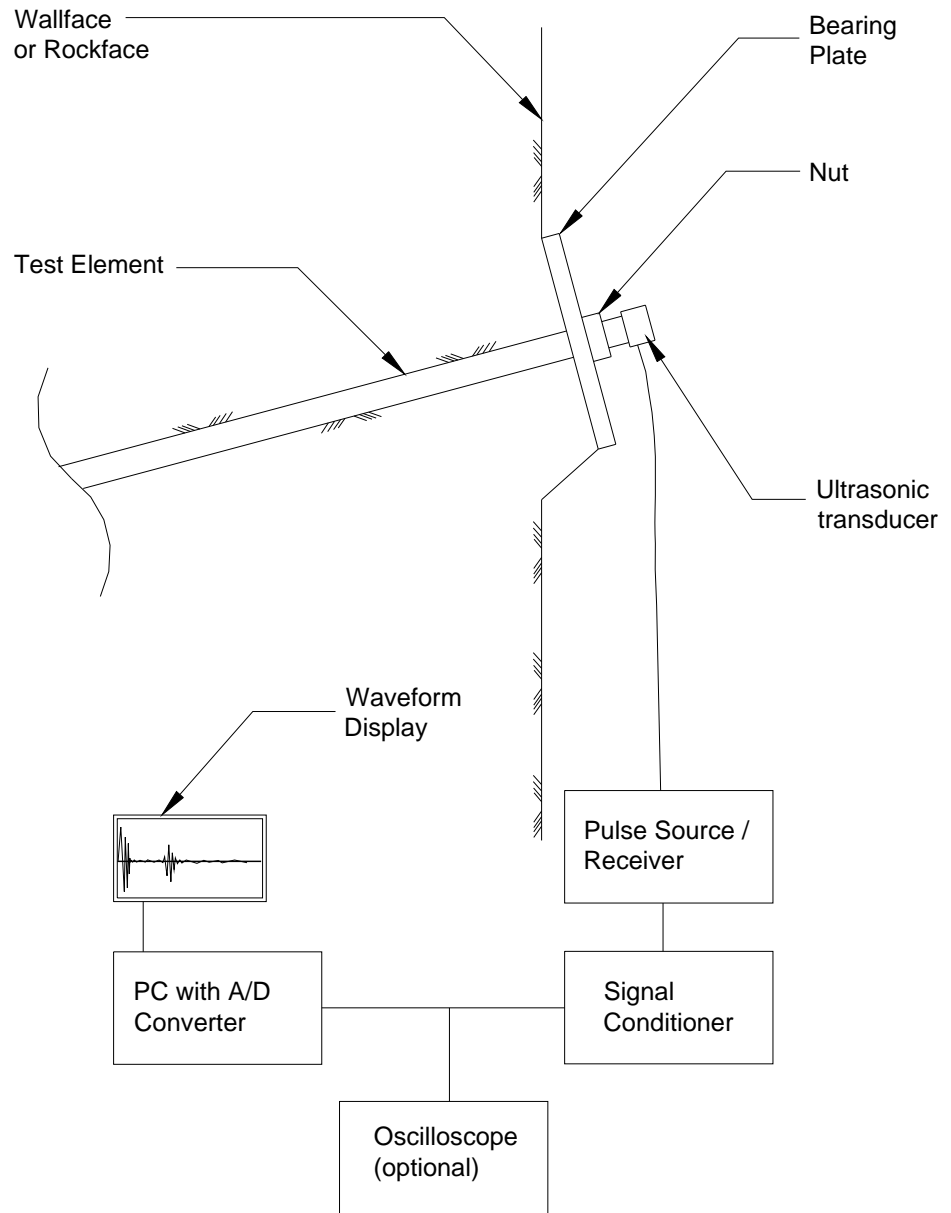


FIGURE 5 Schematic of Ultrasonic Test

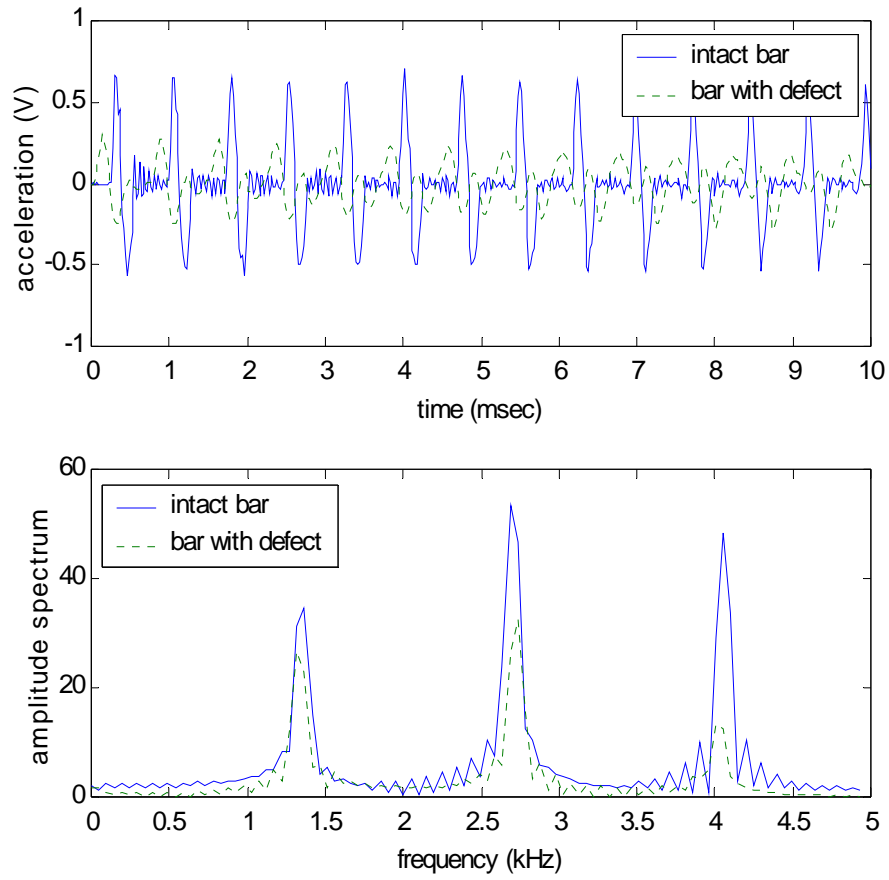


FIGURE 6 Time and frequency-domain response for impact test on 2.0m long intact bar and bar with defect (25% section reduction and 75mm long notch in the middle)

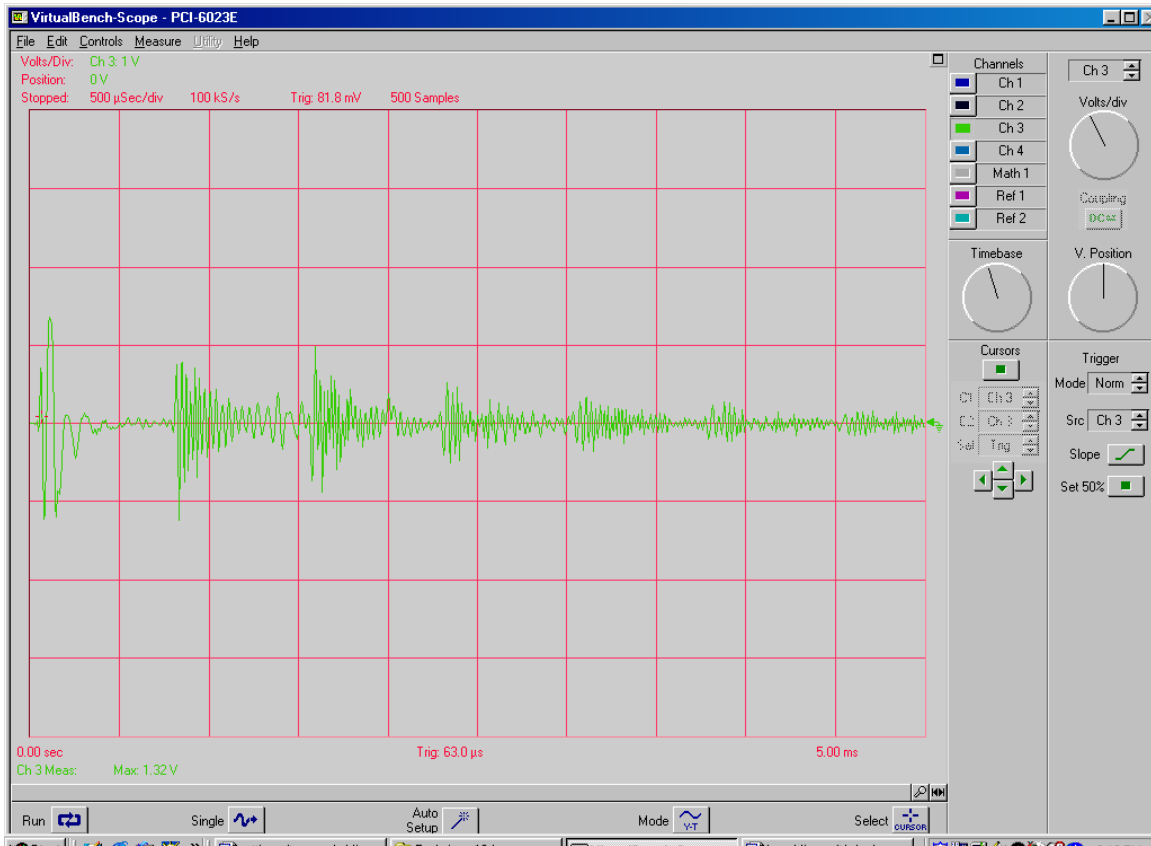


FIGURE 7 Ultrasonic test results for bench-scale 2 m long plain bar without defect

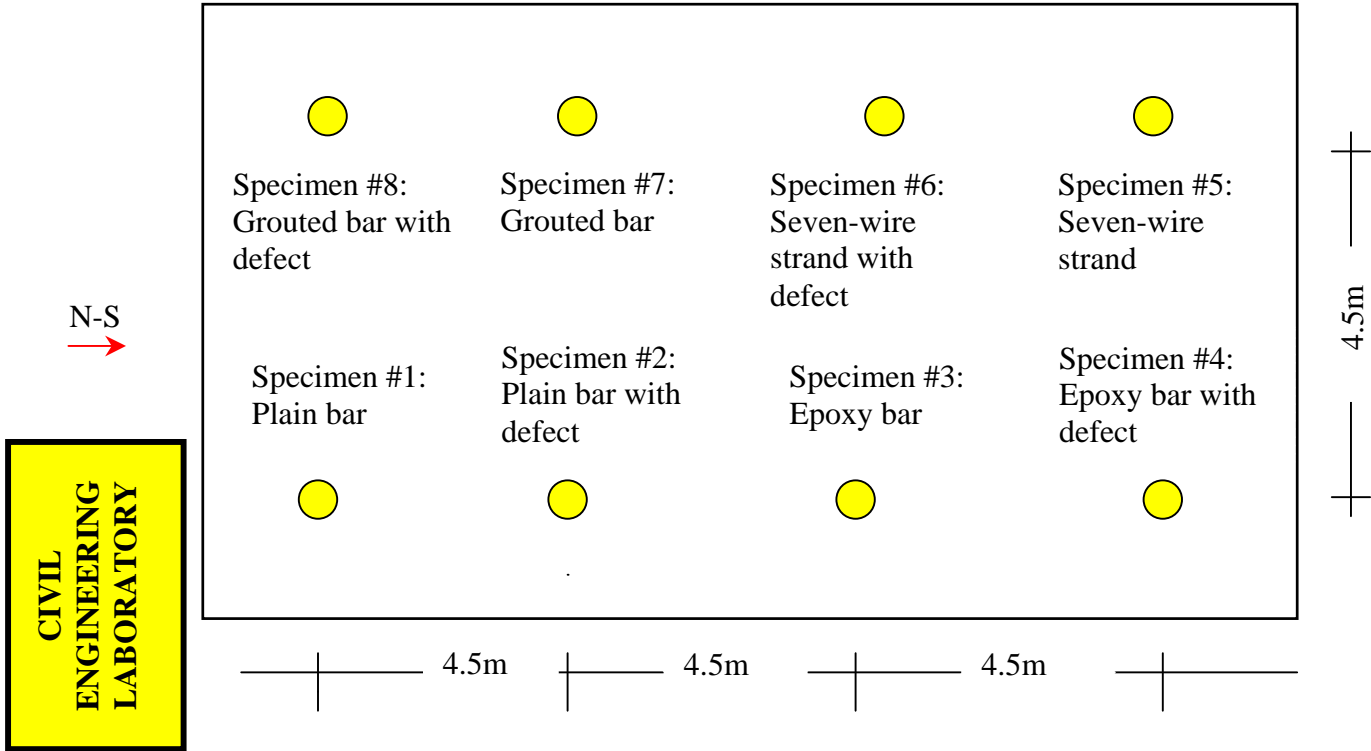


FIGURE 8 Plan view of in-situ specimens



FIGURE 9 Thirty-three year old bars, backfilled in free draining gravel behind the old quay wall, and unearthed at the Buffalo Inner Harbor Project

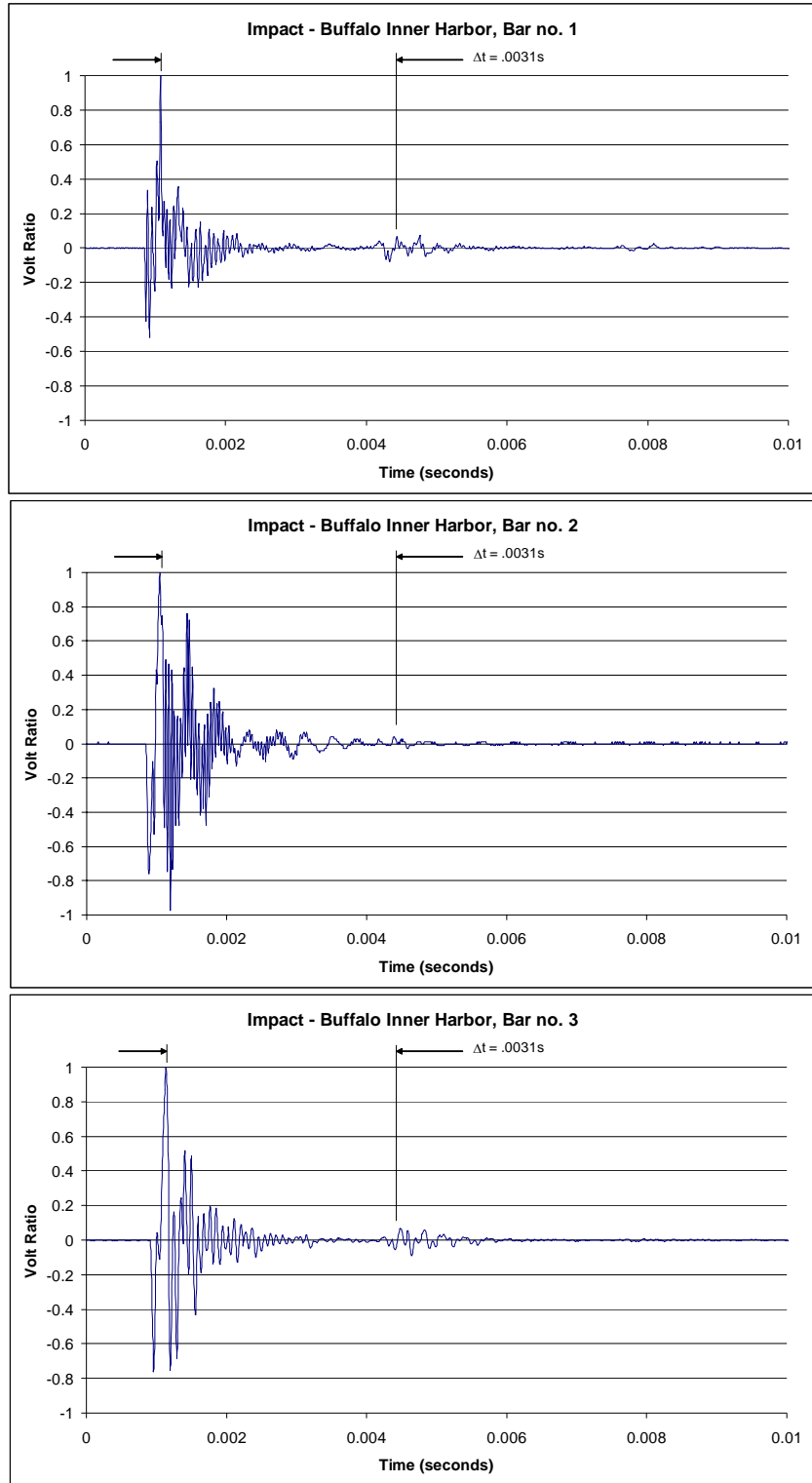


FIGURE 10 Comparison of time-histories from impact tests performed on Bars Nos. 1-3 at Buffalo Inner Harbor

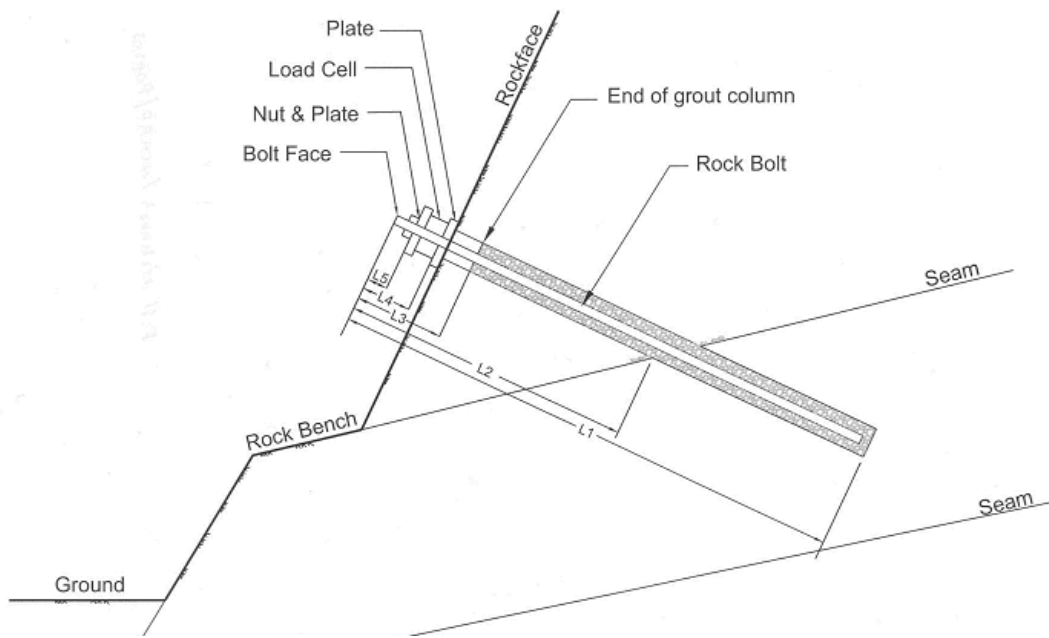


FIGURE 11 Schematic of rock bolt at Dresden, NY

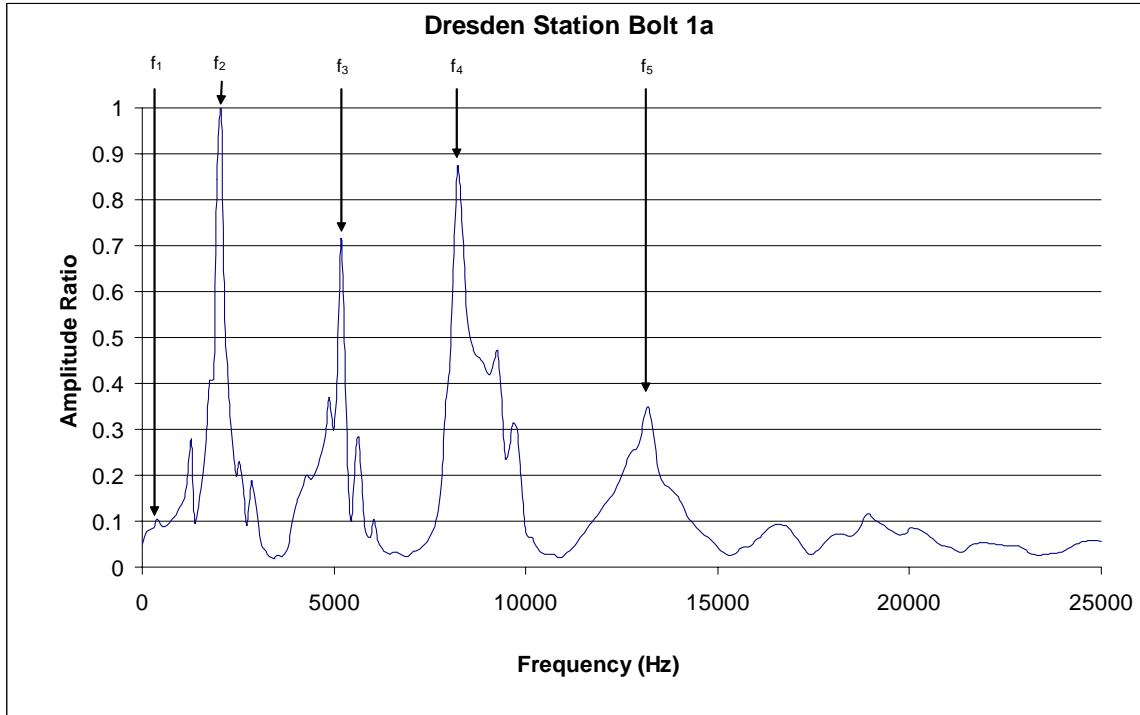


FIGURE 12 Typical frequency response from impact tests on rock bolts at Dresden, NY