This is the pre-peer reviewed version of the following article:


which has been published in final form at [http://onlinelibrary.wiley.com/doi/10.1002/stc.418/abstract].

This is the first application of PZT sensors in civil engineering using EMI technique.

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**Title:** Practical implementation of piezo-impedance sensors in monitoring of excavation support structures

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Abstract: In the last decade electromechanical impedance (EMI) based monitoring technique using piezoceramic (PZT) sensors have been successfully implemented in health monitoring of lab-sized engineering structures. However its implementation in real life application such as monitoring underground support structures has not been done before. In general, the EMI technique utilizes the unique EMI signature where any changes in the signature during the period of monitoring indicate possible damage in the host structure. This paper presents a part of monitoring results of the soil excavation carried out for construction of new mass road transport (MRT) station in the southern part of Singapore using PZT based EMI technique. The MRT site consists of typical clayed soil of varying properties along the depth of excavation. To prevent the soil collapse during excavation, temporary support structures were laid with suitable monitoring systems. The paper presents the results obtained from PZT sensors and the comparisons with conventional measurement devices. However, there were no damages reported in the structure and hence the PZT sensors which were initially aimed to capture possible damages were used later to capture load variations on the struts due to the surrounding soil.

Key words: electromechanical impedance (EMI), structural health monitoring, real-time, PZT, sensor, strain gauge.

1. INTRODUCTION

Singapore’s economy is supported by a vast network of infrastructural facilities in the form of tall buildings, highways, waterways, underground ways, pipelines etc. The city is attracting many foreigners due to its rapid development in areas of telecommunications, software, ship yards, scientific research etc. Owing to this requirement the government is re-aligning the existing transportation systems and constructing new transit facilities. To ensure safety, the existing or new transit facilities are to be continuously monitored as they involve millions of dollars and public life. In the literature it is shown that there are many traditional [1-2] and modern [3-7] safety monitoring methods which can be employed from the beginning of construction stage [8].

Recently, the electromechanical impedance (EMI) technique using piezoceramic (PZT) sensors has been successfully implemented in health monitoring of engineering structures
In the EMI technique, the PZT sensor is either surface bonded or embedded inside the host structure, where PZT is connected to an impedance analyzer using an input/output wire. The governing principle is that the PZT sensor actuates harmonically for a frequency range in the presence of electric field to produce a structural response, which in turn induces the electromechanical (EM) admittance signature of the PZT sensor. The signature consists of real and imaginary parts known as conductance and susceptance respectively. The EM admittance signature is a function of loading [13], stiffness, mass, damping [14] and boundary conditions [12] of the host structure as well as the mass [15-16], length, width, thickness and orientation of the PZT sensor [17]. The changes in the signature are indication of the presence of damages in the structure. It is also shown that PZT is very effective in determining damage location, severity and propagation [18-23] within its sensing range [20].

Many PZT-structure interaction models have been developed for lab-based one dimensional (1D) [21], 2D [22-25] and 3D [26] engineering structures. However PZT based monitoring poses always a challenge [27-28] in real applications. The transformation of lab based monitoring method to real life application [29-30] is not very smooth as expected, especially for civil engineering structures. Furthermore civil engineering structures are often subjected to dead or live loads and within reasonable limits of loadings the occurrence of damages may be ruled out. For such situations damage sensing methods can be employed for load monitoring [31] as presented in later section of this paper. In the present monitoring of excavation support structures, there was no damage found in the structure and hence the PZT sensors which were initially aimed to capture possible damages were used later to capture load variations in the struts due to the surrounding soil. In the literature, it was shown that PZT sensors can withstand monotonous and cyclic loading [32] and PZT based EMI can also be effective in load monitoring [33-34].

This paper presents a part of monitoring results of the soil excavation using PZT sensors for construction of a mass rapid transport (MRT) station in the southern part of Singapore (Figure 1a). The MRT site consists of typical clay soil of varying properties along the depth of excavation. To prevent the soil collapse during construction, temporary support structures comprising of sheet piles, struts and waler beams were laid with suitable
monitoring systems. These systems comprised of measuring instruments, conventional strain gauges, fibre bragg grating (FBG) and PZT sensors, and long input/output cables connecting measuring instruments and sensors (Figure 1b). The measuring instruments, i.e., FBG interrogator, PZT impedance analyzer and strain gauge data logger were kept in air-conditioned site office, whereas the FBG, PZT sensors and other conventional strain gauges were surface mounted on the temporary structures at the excavation site. This paper presents the results obtained from the PZT sensors (Figure 2) and their comparisons with the conventional strain gauges. During the excavation, the surrounding soil exerts load on the support structures, thus causing changes in the PZT signatures without damages in the support structures. Moreover in this site application, very long input/output wires were used to connect the monitoring instrument (PZT impedance analyzer) [35] and the PZT sensors, which were otherwise connected using 1 m wires in laboratories.

Figure 1: Plan and side views of struts installed at MRT station
(a) Singapore map with CCL marking (b) Photographic view of struts
2. DESCRIPTION OF SITE CONDITIONS

Recently, Singapore successfully finished an MRT project for North East Line included the construction of two underground stations [36]. CirCle Line (CCL) is the fourth MRT underground line with an estimated budget of over S$ 6.8 billion, which is currently...
under construction in Singapore. As the name CCL implies, it will be an orbital line linking all radial lines leading to the city (33.3 km long with 29 stations), which covers many parts of the southern area of Singapore and is expected to be completed by 2012. Telok Blangah site is the construction site of one such underground stations (Figure 1a). Depth of the site excavation was around 18 m deep, covering an area of approximately 4500\text{m}^2 (Figure1b). Excavation was carried out in stages from west to east (i.e gridlines 1-15) and steps from level S1 to S4 (see Figures 1a and 2). The site consists of typical clay soil (loose fill 3m, peaty clay 4.5m, hard clay 2.5m) of varying properties along the depth of excavation (Table 1).

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Unit</th>
<th>Soil Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\gamma_{sat}$</td>
<td>kN/m$^3$</td>
<td>18</td>
</tr>
<tr>
<td>Young's Modulus ($E$)</td>
<td>kN/m$^2$</td>
<td>1.5E4</td>
</tr>
<tr>
<td>Poisson's ratio ($\nu$)</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Cohesion ($c$)</td>
<td>kPa</td>
<td>50</td>
</tr>
</tbody>
</table>

The soil at depths greater than 10 m is stiff, consistent and strong (similar to rock, depth of 40m). The sheet pile (Table 2) wall surrounding the excavation was extended to the depth of 21.5 m. Four levels of commissioned struts at 20 sections were used to support the sheet piles (Figure 1b). Waler beams were employed to distribute the load exerted by the struts evenly to the walls.
These struts and waler beams at level S1 were fabricated from H-sectioned UC 300x300x100 kg/m (steel of grade 50, Singapore steel code [36-39]), whereas beams for other levels were fabricated from H-sectioned UC 400x400x200 kg/m. The dimensions of the struts were about 400 mm x 400 mm x 13mm x 21mm (depth x width x flange thickness x web thickness, see steel code [36]) whereas the waler beams were of dimensions 350 mm x 350 mm x 12 mm x 19 mm. All these beams were interconnected to distribute the loads imposed by sheet piles wall at each level. However before installing PZT sensors on the struts for monitoring, initial experiments were conducted in laboratories to test the applicability of these sensors using long input/output wires and for obtaining suitable frequency range of excitation as presented in the following section.

### 3. EXPERIMENTAL LAOD ANALYSIS IN LABORATORY

Research on PZT based EMI models were restricted to lab sized structures with one meter input/output wire only [21-27]. For the first time, to validate the use of long...
input/output wire between impedance analyzer and PZT, laboratory tests were carried out on two specimens. In addition, frequency range of excitation employed in the site application needed to be determined. For this purpose, two specimens with surface bonded PZTs were subjected to low magnitude (N) and high magnitude (order of kN) compression. The first specimen was an L-sectioned (angle of 90 degree with equal edges) aluminum beam specimen with properties listed in Table 3 and the second was an I sectioned strut with properties listed in Table 2, as shown in Figure 3. Two PZT sensors of dimensions 10 x 10 x 0.3 mm (PZT A) and 20 x 20 x 1 mm (PZT B) were surface bonded using epoxy adhesive on the two specimens. PZT A was bonded on the mid-span of the L-specimen and PZT B on the mid-span at web centre of the I-specimen using input/output wire of length 200 m and 350m respectively. For the L-specimen manual controlled compression was employed as the compression load employed was in order of N (0 N to 550 N), whereas for the I-specimen, a compression machine was used to achieve a displacement compression rate of 0.2 mm/min because the compression load employed was higher in the order of kN (150 kN-730 kN).
3.1 Frequency Range of excitation

Figure 4a shows the conductance signatures of the L-specimen for the considered frequency range of 0-1000 kHz. However, variations in signatures are observed up to 200 kHz only after which all signatures overlap. Moreover the signatures do not indicate if there is any increase/decrease in the magnitude of conductance as load increases. Figure 4b is the enlarged view of frequency range 150-152 kHz, which shows an increasing trend in magnitude of conductance signature with increase in load. Figure 4c shows the similar conductance signatures of the I-specimen for different loads within frequency range of 30-110 kHz. It is observed that the magnitude of conductance increases with the load, similar to Figure 4b. To further study the frequency range, statistical root mean square deviation (RMSD) index [40] was employed for two frequency ranges of the first specimen, i.e., for 0-1000 kHz and 150-152 kHz as shown in Figure 5. Figure 5a shows that in the range of 0-1000 kHz, there is not any increasing trend of RMSD as load increases. However there is an increasing trend of RMSD as load increases for the range of 150-152 kHz, as shown in Figure 5b. From these lab experiments, it can be observed that there exists a trend of continuous increase in the magnitude of conductance and RMSD as the load increases if suitable frequency range is adopted.
3.2 Long Input/Output Wires

Another important factor which influences the EM admittance signatures is the length of input/output wires connecting the impedance analyzer and the PZT sensors. To verify the influence of different wire lengths, an experiment was carried out by obtaining three free
signatures for PZT B with different lengths of wire. The type of PZT sensor employed was of the same dimension and property (Table 3) as those to be used in the site. However, the PZT sensor was not bonded on any structure i.e., it was left free with free-free boundary conditions [24] but the PZT was protected (using silicone resin and aluminum cover on the top surface as given in next section). Figure 6 shows the conductance signatures for 40 m, 240 m and 400 m length of the wires. The figure shows that even though the frequency range adopted is the same, there were 1, 3 and 2 peaks for 40 m, 240 m and 400 m wires respectively. It can also be seen that the position of major peaks and their magnitudes change with the length of wire. From these laboratory experiments it can be understood that PZT sensors can be suitably employed for real applications with long wires. However, it is very important to choose a suitable frequency range and length of input/output wires for monitoring.

Figure 6. Conductance signatures for various lengths of input/output wires conducted in laboratory.

(a) One peak signature for 40m length of wire
(b) Two peaks signature for 240m length of wire
(c) Three peak signature for 400m length of wire

Table 3. Key properties of epoxy adhesive, aluminium cover and PZT sensor

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>Epoxy</td>
</tr>
<tr>
<td></td>
<td>1180</td>
</tr>
<tr>
<td>Young’s modulus (N/m²) x 10⁹</td>
<td>2</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.4</td>
</tr>
<tr>
<td>Loss Factor, η</td>
<td>-</td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
</tr>
<tr>
<td>Piezoelectric strain coeff.</td>
<td></td>
</tr>
<tr>
<td>d₃₁ (m/V) x 10⁻¹⁰</td>
<td>-2.10</td>
</tr>
<tr>
<td>Piezoelectric strain coeff.</td>
<td></td>
</tr>
<tr>
<td>d₃₃ (m/V) x 10⁻¹⁰</td>
<td>4.50</td>
</tr>
<tr>
<td>Dielectric loss factor, δ</td>
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</tr>
<tr>
<td>Electric permittivity, ε₃₃</td>
<td>0.98</td>
</tr>
</tbody>
</table>

4. PZT PROTECTION AND INSTALLATION ON STRUTS

The PZT sensors supplied by PI ceramic [41] for the present project were of dimension 20 x 20 x 1 mm with properties listed in Table 3. These PZT sensors were naked without protection to withstand the harsh site conditions. Thus, protection case was prepared using aluminum cover and RTV elastoplastic silicone resin (grade: 3140-MIL-A-46146, [42]), as shown in Figure 7a. The figure shows the schematic representation of the layers used for protection. On the top surface of the PZT sensor, two wires were soldered on respective slots which provide the power supply to the sensor. Later, 2 mm thick RTV silicone coating was uniformly applied; over which an aluminum cover of approximately of 30 x 30 x 1 mm was bonded as shown in the figure. The use of softer RTV coating is
necessary to reduce the damping caused by mounting a stiff aluminum cover on the sensor. This was allowed to cure for at least 24 hours after that, the PZT sensor is now considered to be sufficiently protected with aluminum cover on top, and the bottom surface of PZT is ready for mounting on the structures. Throughout our studies, we have found that this method of protecting the PZT sensors offers the best protection during the course of their transportation, installation and service life. Later, these protected PZT sensors were bonded on the struts using epoxy adhesive (Table 3) and were left for curing for 24 hours before using them for monitoring.
Figure 7: Installation of PZT sensor on the strut
(a) Schematic representation of fabricated PZT sensor
(b) Use of magnetic strips to align PZT on vertical surface
(c) PZT sensors bonded on web and flange of the strut
(d) Ready to use PZT sensors on the strut

A total of 24 protected PZT sensors were fabricated for installation on twelve locations as shown in Figure 2 at struts NS-9 and 14 for levels S1 and S2 (where NS represents north-south direction of the strut, and 9 and 14 represent the number of the strut). At each location two PZT sensors were installed, one on the web and other on the flange section of the strut as shown in Figure 7. Figure 7b shows the use of flexible magnetic strips (weight of about 100 grams) to temporarily adhere the PZT on the vertical surface, i.e., on the web. As a preventive measure, the magnetic strip was orientated at right angle to gravity to prevent any excess epoxy adhesive, from coming into contact with the magnet. This magnet strip was removed after the curing of epoxy on vertical surface. However, the PZT sensors were much easily to be bonded on flange section of the struts and the bonded PZT sensors were shown in Figure 7c. A protective polyvinyl chloride (PVC) housing was used for additional safety to avoid rain water stagnation, as shown in Figure 7d. Subsequently, the PZT sensors were tested to ensure that they are working. Lastly, silicon rubber was applied at the edges of the sensor to seal any gap between the sensor and PVC housing.

5. MONITORING RESULTS AND DISCUSSIONS

5.1 Conductance Signatures

The distance between the excavation site (location of sensors) and the site office (location of measurement instrument) is around 20 meters from gridline 1 as shown in Figures 1b. The choice of the strut at gridline 7 (NS-9) was made primarily due to the fact that the strut at this section of excavation was the longest (34.5 m) and with lacings. While the strut at gridline 10/11 (NS-14), was selected for monitoring because it was one of the shortest struts (24.2 m). The input/output wires used for PZT sensors at level NS-9 and NS-14 are of length about 250 and 400 meters respectively. From past experience and
laboratory experiments, the frequency range of monitoring adopted was 50–150 kHz because within this range it was observed that the magnitude of conductance signatures increased with the load on struts. The monitoring period (time) adopted was different for different struts depending on excavation procedure. The excavation was carried out in stages (gridline 1 to 15) and levels (level S1 to S3). After level S1 was excavated, struts at that level were installed and then they were preloaded to the pre-set value, after which measurements of PZT sensor were carried out. For this level almost 11 months of monitoring from July 2006 to June 2007 was carried out for PZT 1 to 12 (Figure 2). After first month of monitoring, struts at level S2 were installed and subsequently PZT 13 to 24 were instrumented and signatures were obtained for the next 10 months from August 2006 to June 2007. All these signatures were automatically recorded by operation software in a PC which controls the impedance analyzer in the site office for pre-defined dates and time. For all the PZT sensors, the first day signatures were considered as the baseline signatures. They were then compared with signatures of later dates and a total of 24 monitoring graphs were obtained for all the 24 PZT sensors. Moreover, in order to clearly understand the monitoring results, statistical RMSD index [40, 43] was employed to analyze all the conductance signatures.

Figure 8 shows some representative monitoring results for a period of 10 days for PZT 1, 3, 6 on strut NS-9 and PZT 9, 11 and 12 on strut NS-14 for level S1. All the 24 monitoring graphs during the entire monitoring period had shown either one, two or three peaks in signatures as similar to Figure 8 (also as similar to laboratory tests, see Figure 6). The variation in number of peaks and magnitude of the signature is due to the different length of wires used. Increase in wire length yielded a lower magnitude peak and a left shift of prominent peak. For example, comparison between PZT 6 (Figure 7c) and PZT 1 (Figure 7a) shows that a longer wire yielded lower magnitude of peak as compared to a shorter wire. It should be noted that PZT 1-6 were installed on the same strut which carried same axial load. Similarly, 400m length of wire (Figure 8e) yielded lower magnitude of peaks compared to shorter wires (Figure 8c).
Figure 8. Conductance signatures of PZT sensors from Dec 9 to 18, 2006 for level S1

(a) PZT 1 using 300 m of cable (b) PZT 3 using 245 m of cable
(b) PZT 6 using 250 m of cable (d) PZT 11 using 350 m of cable
(a) PZT 9 using 350 m of cable (f) PZT 12 using 400 m of cable

5.2 Local and Permanent Disturbances during Monitoring Period

Data acquisition of the 24 PZT sensors were carried out between 10am-2pm daily and the air temperature in Singapore was usually between 26-34 °C. Even though the temperature had not affected the monitoring signatures significantly [44], the site disturbances due to either personnel or machine traffic had influenced them. The two basic disturbances namely local and permanent disturbances in the signatures were observed for some PZT sensors. Figure 9a-b shows the sample conductance signatures observed for some PZT sensors. The occurrences of local disturbances can be captured by the additional peaks in the signatures as similar to that for day 2 shown in Figure 9a. These disturbances can occur due to the presence of extra materials or hammering nearby the location of PZT sensor. However, after the removal of these disturbances the signature comes back to
normal as similar to that of day 3. This is evident from Figure 8b, where the conductance signature depicted on 12 and 14 Dec. 2006 had shown disturbances, which was not present on other days. Further, Figure 9c shows the RMSD plot for PZT 4 installed on the flange of strut NS-9 at level S1 with three local disturbances during its period of monitoring. This PZT was located at mid-span of the strut and it was near to the junction of waler beam and strut, and hence the chance was high because of installation/removal of some fixtures which were temporary.

Permanent disturbances can occur as shown in Figure 9b, i.e., after day 3 there was a sudden drop in magnitude of signature and then after 3 more days there was a sudden rise. Such disturbances can occur due to permanent fixing/removing of heavy object from vicinity of the PZT sensor. These permanent disturbances were noticed in signature obtained by PZT -15 which was located at mid-span on web of NS-9 level S2, as shown in Figure 9d. Even though huge strutting disturbances were reported during that period of monitoring nearby the location of PZT sensor but it is still difficult to identify the actual cause.
Figure 9. Local and permanent disturbances produced in some sensors

(a) Sample signatures with local disturbances
(b) Sample signatures with permanent disturbances
(c) Local disturbances observed in PZT 4 at mid span of strut NS-9 for level S1
(d) Permanent disturbances observed in PZT 15 at mid span of strut NS-9 for level S2

5.3 Comparisons of PZT and Strain Gauge Results

Figures 10-13 show the comparisons between strain gauges and PZT sensors located at the mid span on web sections of struts NS-9 and NS-14 for S1 and S2 levels. For these figures, monitoring period was denoted on the X axis and, strut load and RMSD obtained from strain gauge and PZT sensor respectively were denoted on the Y axis. During the period of monitoring, no damages in the support structures occurred. However, the loading on the beams and struts were observed to increase during initial stages as anticipated and after that the loading was stabilized to more or less constant value.
In the laboratory tests, for the I-specimen the RMSD value was found to increase with increase in loading on strut (see Figures 3-4). Thus it was believed that RMSD is proportional to strut load (see Figure 5) for the considered frequency range. Hence, even though the Y axis for strain gauges and PZT sensors are different, they were still used for comparison of trends. The comparisons revealed that more or less strain gauges and PZT sensors had followed the similar pattern of load increase or decrease during the period of monitoring.

Figure 10. Comparison between results of strain gauge and PZT for NS-9 (level S1) at mid-span location (a) Strut load variation of strain gauge (b) RMSD variation of PZT sensor
Figure 11. Comparison between results of strain gauge and PZT for NS-9 (level S2) at mid-span location (a) Strut load variation of strain gauge (b) RMSD variation of PZT sensor

Figure 12. Comparison between results of strain gauge and PZT for NS-14 (level S1) at mid-span location (a) Strut load variation of strain gauge (b) RMSD variation of PZT sensor
Figure 13. Comparison between results of strain gauge and PZT for NS-14 (level S2) at mid-span location (a) Strut load variation of strain gauge (b) RMSD variation of PZT sensor

Usually RMSD index do not have negative value, but for comparisons with strain gauges the negative and positive RMSD scale on Y axis was used in the Figures 10, 11 and 12. The comparisons show that for strut NS-9 at level S1, one RMSD unit is approximately equivalent to 40 kN. For strut NS-9 at level S2, one RMSD unit is approximately equivalent to 500 kN. For strut NS-14 at level S1, one RMSD unit is equivalent to 20 kN. Similarly for strut NS-14 at level S2, one RMSD unit is equivalent to 30 kN. However as previously shown (Figure 6) in laboratory experiments that the position of peak and their magnitudes depend on length of wires, the RMSD value also varies with the length of input/output wire. Additionally, it should be noted that the baseline signature, time, and frequency range (Figure 5) determines the RMSD unit for the strut. To successfully implement PZT sensors for large scale load monitoring, proper length of wire needs to be carefully selected because longer than necessary length of wire will reduce the accuracy of the results.
6. CONCLUSIONS

This paper presents a part of monitoring results of the soil excavation carried out for construction of a new MRT station in the Telok Blangah district of Singapore using PZT based EMI technique. The PZT sensors which were initially aimed to capture possible damages were used later to capture load variations in the struts due to the surrounding soil. The surrounding soil acted as load which causes the changes in the PZT signatures without damages in the structure. For the first time, long input/output wires were used to connect monitoring instrument and the PZT sensors, which were otherwise connected using 1m wires in laboratories. The results show that PZT sensors are effective in load monitoring even by using very large input/output cable lengths. The PZT can provide complementary results as they can indicate local or permanent disturbances in the structures. In future PZT sensors can be groomed for practical applications without much difficulty as there comparisons with conventional strain gauges were found to be satisfactory. This paper is hence expected to be very useful for PZT based monitoring applications in real life.

Acknowledgements

The authors would like to acknowledge The Enterprise Challenge, Prime Minister’s Office of Singapore for funding the project. They would also like to thank their research collaborators from LTA, DSTA, SIF-universal Pte Ltd, and Tritech Engineering and Testing Pte Ltd.
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This is the pre-peer reviewed version of the following article:


which has been published in final form at [http://onlinelibrary.wiley.com/doi/10.1002/stc.418/abstract].

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