The concept of sustainability arises because of the finite and limited resources of the world. This limitation is exacerbated by the continual growth of the world’s population, whose demand on resources increases significantly with time. To overcome this problem, sustainable development, which is defined in the Brundtland Report as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” is imperative. It refers to the optimal utilization of these resources with the aim of maximizing their usage effectiveness while at the same time minimizing the adverse effect of their use on the environment. This includes conservation and enhancement of resources by gradually changing our approach towards the development and utilization of technologies. The principle of sustainability must be translated into practical engineering projects; otherwise, resources may be completely depleted or the environment may suffer irreversible damage.

In a discussion paper\(^1\) presented by the President of the Institution of Professional Engineers New Zealand (IPENZ) under the auspices of the IPENZ Presidential Task Committee on Sustainability in 2003-04, four key sustainability factors for engineers in the profession were identified:

1. To manage changes in the environment (both local and global) resulting from engineering activities which threaten the continued viability of the planet;
2. To ensure the equal distribution of resources and safety of engineering activities for both current and future generations;
3. To ensure that the skills of professional engineers in problem solving are carried out holistically; and
4. Where practicable, to make good existing problems caused by past failures to follow sustainability principles.

The School of Civil and Environmental Engineering endorses the principle of engineering for sustainability. On the one hand, it inculcates this principle in both her under-graduate and post-graduate students so that they will become engineers with this mindset. The School believes that it is crucial to educate young engineers in this approach from the start so that they will be committed to implement sustainable development.

Research in the School is also carried out using a similar approach so that new and novel ideas are developed for use by the practicing community to promote sustainability. Past environmental failures that were considered technically and economically impractical to remedy are re-examined in innovative research endeavors to determine if they can be resolved. Multi-faceted approaches are investigated in depth by inter-disciplinary team members for innovative ideas which ensure a holistic solution to engineering practices. Thus, a mono-faceted approach with a solely technical view point is discarded in preference to a synergistic approach. Such cooperation amongst researchers from different fields is crucial in ensuring a better understanding of the complexity that exists in a fast changing environment, both at the local and global level. Only with such knowledge can one manage the threat to Earth from, for example, global warming and the consequent rise in sea-level. The optimal use of diminishing resources in the 21\(^{st}\) century demands novel ideas beyond classical solutions. Renewable resources and recycled material, which are becoming crucial in everyday engineering practices, are examined and tested by teams in the School to ensure a level of safety that does not endanger public health.

This article summarizes some of the research currently undertaken in the three Divisions of the school, namely,

- Division of Environmental and Water Resources Engineering (EWRE)
- Division of Infrastructure Systems and Maritime Studies (ISMS)
- Division of Structures and Mechanics (SM)

Some of the research programs in progress are as follows:

- Environmental Monitoring towards Sustainability (EWRE)
- Membrane Research (EWRE)
- Recycling and Waster Resources (EWRE)
- Risk Assessment in Sustainable Public Private Partnership (PPP) Infrastructure Projects (ISMS)
- Sustainable Transportation System (ISMS)
- Utilization of Underground Space (ISMS)
- Continuous Structural Health Monitoring using Smart Sensors (SM)
- Safety and Risk Assessment of Offshore Structures with Cracks and Defects (SM)
INTRODUCTION

In load-out operations, the ballast plan is generally calculated by assuming a rigid barge. The objective of the ballast plan is to maintain the deck of the barge horizontally levelled with the yard, while the load-out progresses. However, in reality, the barge is flexible and there is also foundation settlement at the yard. Excessive deflection and settlement may cause the loaded-out structure (hereafter also called the jacket) to be overstressed. Assuming a rigid barge and no yard settlement is only justified provided the deflection of the barge and the settlement of the yard are small such that they can be neglected. Without this justification, calculation done based on the assumption of a rigid barge and/or no yard settlement is not realistic and may cause damage to the jacket structure and/or the barge.

In order to represent the actual load-out operations better, a more realistic ballast calculation method which also has the prospect of reducing the effort taken is proposed. In the method, the flexibility of the barge from the outset which is different from the traditional method [1] is taken into account. The theory of beam on elastic foundations is adopted to model the load-out process. To find the optimum ballast plan, a multi-objective evolutionary algorithm (MOEA) is used. The algorithm is designed to find an optimum ballast arrangement at each load-out stage, which should minimize the deflection of the jacket and/or barge and the amount of ballast that has to be removed or shifted from the previous load-out stage to the current one. An optimum ballast plan for the whole load-out operation will be a set of optimum ballast arrangements for all the load-out stages. The simplified beam-on-elastic-foundation model and the optimization algorithm form the two cores of the proposed method.

BEAM-ON-ELASTIC-Foundation MODEL

We simplify the analysis of the load-out process into an analysis of a 2-dimensional beam-on-elastic-foundation model (see Figure 1). This simplification is made possible by assuming that the geometry and the loading of the jacket and the barge are always symmetrical about the centre line dividing the port and starboard sides of the barge, and that there is only longitudinal variation of ballasts in the barge. It is assumed that the jacket is oriented with its base toward the water. We also assume that all ballast tanks have equal lengths. The analysis is static; wind, wave, current, and impact forces are neglected. Initial deformations of the barge are also neglected. However, tide variation is accounted for.

The Winkler theory of beams on elastic foundation is adopted. The differential equation for the deflection of the beam is

\[ EI \frac{d^4 y}{dx^4} = -ky + q, \]  

where \( k \) is the foundation stiffness and \( q \) is the distributed load acting upon the beam. Some part of the beam rests on the yard with foundation stiffness \( k_1 \), and the remaining part rests on water with hydrostatic stiffness \( k_2 \). We assume a trapezoidal loading due to the jacket weight, which can be separated into a uniformly distributed loading and a triangular loading.

The deflection of the beam can be obtained using the method of superposition outlined by Hetényi [2]. The beam is cut into three segments, each having different moduli of elasticity and area moments of inertia, as shown in Figure 2. Segment \( I \) is defined as the part of the jacket that rests on the yard, segment \( II \) as the part of the jacket on the barge, while segment \( III \)
remaining part of the barge. We first find the moments and shearing forces produced at the end points of each segment, assuming an infinitely long beam. Next, the end-condition forces are applied to satisfy the required conditions at both ends of the segment, which is free at both ends. Then, the displacements and slopes at the cutting points between segments are found. Knowing the relative displacement and slope difference between the ends of the neighboring segments, the shearing force $X$ and moment $Y$ at each of the cutting points to bring about and maintain the continuity of the beam are determined. Finally, having obtained the shearing forces and moments, the deflection of the beam at $x$ is obtained.

**Multi-Objective Evolutionary Algorithm (MOEA) for Finding Optimum Ballast Plan**

An optimum ballast arrangement will be one that meets the following objectives: (1) it should minimize the deflection of the jacket and/or the barge, and (2) it should also minimize the amount of ballast that has to be removed or shifted from the previous load-out stage to the current one. It should be noted, though, that a ballast arrangement which satisfies the first objective does not necessarily satisfy the latter. In other words, the objectives could be conflicting, and therefore it is likely that there are more than one optimum solution to the problem, which satisfy the objectives in a trade-off manner. When more than one objective is involved in an optimization problem like this, the task of finding the optimum solutions is known as multi-objective optimization. In our case, it is a multi-objective optimization problem (MOOP) with two objectives.

**Formulation of the multi-objective optimization problem**

We assume that initial ballast is already applied such that it balances the buoyancy force from the water, for a given draft. The initial ballast is calculated as follows. The minimum draft of the barge $d_{min}$ is first calculated as

$$d_{min} = \frac{w_{\text{barge}}}{k_2},$$

where $w_{\text{barge}}$ is the weight of the barge. Given the draft $d$ of the barge, which has to be greater than $d_{min}$, the buoyancy of the water $F_b$ can be calculated as

$$F_b = k_2 d.$$

The initial ballast needed to balance the buoyancy force is therefore

$$w_i = F_b - w_{\text{barge}},$$

and the initial ballast height is

$$h_{\text{init}} = \frac{w_i}{k_2}.$$

We use a non-dimensional value, $\alpha_i$, $i = 1, 2, ..., n$ (where $n$ is the total number of ballast tanks) to represent the ballast weight $w_i$ in tank $i$. $\alpha_i$ has a value from 0 to 1, and is related to $w_i$ as follows:

$$w_i = (\alpha_i h_b - h_{\text{init}}) k_2,$$

where $h_b$ is the height of the ballast tank. It is this $\alpha = (\alpha_1, ..., \alpha_n)$ which we seek to optimize.

The MOOP can therefore be formulated as follows:

For $0 \leq \alpha_i \leq 1$,

$$\min_{\alpha} f_i(\alpha) = y_{\text{rms}},$$

minimize

$$f_2(\alpha) = \begin{cases} \frac{\sum (\alpha_i' - \alpha_i)}{\sum h_{\text{init}} - h_{\text{init}}} & \text{if } \sum \alpha_i \leq \sum \alpha_i' \\ \frac{\sum (\alpha_i' - \alpha_i)}{\sum h_{\text{init}} - h_{\text{init}}} & \text{if } \sum \alpha_i > \sum \alpha_i' \end{cases},$$

where the first function is the root-mean-square of the deflection of the beam model. The second function is the function to calculate the amount of ballast that has to be removed or shifted from the previous stage to the current one. The prime (’) denotes the value at the previous stage. The expression for the function is formulated assuming the ballast in one tank can be transferred to every other tank with equal speed.

To find the solution to the above MOOP, a multi-objective evolutionary algorithm (MOEA) is developed. Evolutionary
algorithm (EA) is a stochastic optimization method which processes a population of solutions throughout its iterations. This population approach is the distinctive feature of an EA and is well suited for finding a number of optimum solutions. For a comprehensive overview of MOEA the reader is referred to Deb [3].

RESULTS AND DISCUSSIONS

A load-out case study is carried out and it is assumed that there is no tide variation. The load-out process is divided into Stages 0 to 30. The incremental progress of the jacket on the barge from one stage to the next is 5 m, except for Stage 0 to 1, which is 1 m. Optimum ballast arrangements obtained for stages 21 to 30 in terms of $\alpha$ values are shown in Figure 3, while the deflections of the beam for the optimum ballast arrangements for stages 17 to 30 are shown in Figure 4 and Figure 5, respectively.

It is observed that the ballast arranges itself in a sinklike form to counter the jacket load at the earlier stages. As the jacket progresses, the sinklike form becomes more evident and moves to the right. Comparisons with results obtained with the assumption of a rigid barge will provide further justification for the advantage of this method. Also, with MOEA, modifying or adding objective functions can be done with ease. Interesting comparisons can be made between results obtained by minimizing the beam deflection and those by minimizing the beam curvature. It is even possible to obtain results which minimize both the beam deflection and curvature.

ACKNOWLEDGEMENTS

Research grant from Maritime and Port Authority Singapore is gratefully acknowledged. The authors would also like to thank Falconer Bryan Pte Ltd for providing an actual load-out report.
Structural health monitoring using PZT transducers based electromechanical (EM) impedance of structures is fast emerging. The transducers are surface bonded to or embedded into the host structure and subjected to electric actuation. The actuation results in the EM admittance (EMA) signatures that serve as indicator to predict the health/integrity of the host structure (Yang et al. 2005; Annamdas and Soh 2007). However in real life, the structural components such as slabs, beams and columns are constantly subjected to some forms of external loading. The EMA signature obtained for such a structure is different from the one obtained when damages are present in the structure. This study attempts to demonstrate the effect of loading on the EMA signature by experiment.

EXPERIMENTAL TEST AND RESULTS

Three different lab-sized specimens are tested with various magnitudes of external loading. For the simply supported and centre-loaded beams in this experiment, the maximum bending moment occurs at the centre of the specimen, where the PZT transducers are bonded. Figure 1 schematically illustrates the experimental setup. Table 1 lists the maximum stresses experienced by each of the specimen under different loadings.

The EMA is a function of PZT and structural properties. Especially, it is sensitive to the dynamic stiffness of the structure. The stress induced by the applied load will affect the structural dynamic stiffness and the effect will be reflected in the EM admittance signature.

Table 1. Maximum stress values in specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Load (N)</th>
<th>Maximum stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>46.9</td>
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<tr>
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<td></td>
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<td></td>
<td>150</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>200</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Three aluminium beams bonded with three different PZT transducers are tested, with an increment of load 25N at the center (Figure 1). A total of nine EMA signatures are recorded.