INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD)
© 2026 IJNRD | Volume 11, Issue 1, January 2026 | ISSN: 2456-4184 | IJNRD.ORG

Harmonic Response–Based Evaluation of Mass Concrete Foundations for Low-Frequency Rotary Machines Considering Geometry and Rubberized Concrete

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Abstract : Mass concrete foundations are widely adopted for supporting low-frequency rotary machines due to their high inertia and ability to suppress vibration amplitudes. However, foundation performance is strongly influenced by both geometric configuration and material damping characteristics. This study presents a numerical investigation of the steady-state harmonic response of four mass concrete foundation configurations supporting a low-frequency rotary pump: (i) Cuboid Conventional Concrete (CC), (ii) Cuboid Rubberized Concrete (CRC), (iii) Trapezoidal Conventional Concrete (TC), and (iv) Trapezoidal Rubberized Concrete (TRC). Three-dimensional finite element models were developed in ANSYS using SOLID185 elements. Harmonic analysis was performed to evaluate frequency response in terms of directional deformation and maximum principal stress over the operating frequency range of the machine. Results indicate that rubberized concrete significantly reduces peak vibration amplitudes due to enhanced material damping, while trapezoidal geometry improves stiffness and stress distribution. Among the four cases, the trapezoidal rubberized concrete foundation exhibited the lowest deformation amplitude and reduced dynamic stress demand, demonstrating superior vibration control performance. The findings highlight the combined effectiveness of material modification and geometric optimization for safe and efficient design of mass concrete foundations for low-frequency rotary machinery.

***Keywords* - Mass concrete foundation, harmonic analysis, frequency response, rubberized concrete, trapezoidal foundation, low-frequency rotary machine.**

INTRODUCTION

Low-frequency rotary machines such as pumps and compressors generate continuous harmonic forces during operation due to imbalance, fluid pulsation, and rotating components. If not adequately controlled, these forces can induce excessive vibrations in the supporting foundation, leading to resonance, cracking, loosening of anchor bolts, and reduced service life. Mass concrete foundations are commonly used for such machines because their large mass and stiffness help shift natural frequencies away from operating frequencies.

Recent studies have shown that, in addition to mass and stiffness, damping plays a critical role in vibration attenuation. Rubberized concrete, produced by partial replacement of aggregates with rubber particles, exhibits enhanced energy dissipation capacity. Furthermore, geometric modification of foundations, such as adopting trapezoidal shapes, can improve stress distribution and dynamic stiffness. In this context, harmonic response analysis provides a realistic assessment of steady-state vibration behavior under machine operating loads.

This paper focuses on comparative harmonic response evaluation of four foundation configurations by analyzing frequency response of deformation and stress, which are the most critical response quantities governing vibration safety and serviceability of machine foundations.

NUMERICAL MODELING AND FOUNDATION CONFIGURATIONS.

3.1 Machine and Loading

The foundation supports a low-frequency rotary pump with a total operating weight of approximately 30 kN. Harmonic forces corresponding to machine operating frequency were applied at the machine–foundation interface in the vertical direction, representing combined effects of unbalance and fluid pulsation. The analysis was performed over a frequency range covering the operating frequency and its vicinity to capture resonance-sensitive behavior.

3.2 Material Properties

Two material models were considered:

- Conventional M40 Concrete (CC, TC): High stiffness with relatively low inherent damping.
- Rubberized M40 Concrete (CRC, TRC): 10% rubber replacement of coarse aggregate, resulting in reduced elastic modulus but improved damping characteristics.

Linear elastic material behavior with equivalent modal damping was assumed for harmonic analysis.

3.3 Foundation Geometry and Dimensions

Four foundation configurations were analyzed. Dimensions were kept identical at the top to ensure consistent machine support conditions.

Cuboid Foundations (CC and CRC):

- Length: 900 mm
- Width: 600 mm
- Depth: 1800 mm

Trapezoidal Foundations (TC and TRC):

- Top length: 900 mm
- Top width: 600 mm
- Bottom length: 1800 mm
- Bottom width: 1200 mm
- Total depth: 1800 mm (1350 mm vertical + 450 mm sloped portion)

The trapezoidal geometry provides a wider base, improving stability and stiffness while reducing stress concentration.

3.4 Finite Element Model

All foundations were modeled using SpaceClaim in ANSYS. The base of the foundation was assumed to be fixed, representing rigid soil support for comparative evaluation. Harmonic response analysis was conducted after modal analysis to ensure adequate frequency separation from resonance conditions

The study employed ANSYS 2025 R1 to perform a detailed numerical analysis of mass concrete foundations, both rectangular and trapezoidal, supporting a low-frequency rotary machine. The Finite Element Analysis (FEA) was used because it allows accurate modeling of complex geometries, material properties, and dynamic behavior that cannot be easily captured by simplified analytical methods.

4.1. Geometry and Material Modeling:

The foundation and machine base were modeled in 3D. Rectangular and trapezoidal geometries were created according to the design dimensions. The foundation materials were defined as:

- M40 normal concrete: Linear elastic, isotropic, homogeneous material.
- Rubberized concrete: Modeled as equivalent homogeneous material with reduced stiffness and density based on literature correlations.

These simplifications are standard in FEA when a fully numerical study is conducted, as they allow for capturing the essential structural behavior without excessive computational complexity.

4.2. Meshing:

The foundation was discretized using 3D solid elements (SOLID185). Mesh refinement was applied near critical regions such as the machine–foundation interface and corners to accurately capture stress concentrations and local vibration effects. A structured mesh was used where possible to balance accuracy and computational efficiency.

4.3. Boundary Conditions:

Realistic foundation–soil interaction was simulated using:

- Fixed supports at the base for a conservative approximation.
- Elastic supports or springs for modeling soil stiffness (optional depending on scenario).

These boundary conditions ensure that the foundation response is representative of real-world conditions, where the machine rests on a soil-supported concrete block.

HARMONIC RESPONSE ANALYSIS METHODOLOGY

Steady-state harmonic response analysis was carried out to evaluate the vibration behavior of the machine–foundation system under sinusoidally varying dynamic loads corresponding to the operating condition of the low-frequency rotary pump. The analysis aims to quantify how the foundation responds across a range of excitation frequencies and to identify critical frequencies associated with peak vibration and stress response.

3.1 Selection of Response Direction

In rotary machine foundations, vibrations induced by unbalanced forces, fluid pulsation, and thrust loads are predominantly transferred along the vertical (Y) axis, which corresponds to the direction of gravity and the principal load transfer path between the machine and the foundation. As per IS 2974 (Part IV), vertical vibration response is generally the governing criterion for assessing serviceability and resonance safety of block-type machine foundations. Therefore, the harmonic response evaluation in this study focuses specifically on the Y-direction response.

3.2 Frequency Response – Directional Deformation (Y-Axis)

The frequency response of directional deformation along the Y-**axis** was extracted to assess the steady-state vertical vibration amplitude of the foundation under harmonic excitation. Directional deformation represents the displacement of the foundation in the Y-direction at each excitation frequency and is a direct indicator of vibration severity.

For each foundation configuration, the excitation frequency was swept across a predefined range covering the machine operating frequency and its vicinity. The resulting deformation–frequency plots were used to:

- Identify peak vibration amplitudes,
- Examine resonance tendencies,
- Compare vibration attenuation capability of different materials and geometries.

Lower peak deformation amplitudes and smoother response curves indicate better vibration control and reduced resonance risk.

3.3 Frequency Response – Stress (Y-Axis)

In addition to deformation, the frequency response of stress along the Y-axis was evaluated to study the dynamic stress demand induced by harmonic loading. Stress response in the Y-direction is critical because repeated tensile–compressive stress cycles can lead to cracking, fatigue damage, and long-term deterioration of mass concrete foundations.

The stress–frequency response curves were obtained in terms of maximum principal stress associated with Y-direction vibration, allowing identification of frequencies at which stress amplification occurs. This response parameter provides insight into:

- Potential crack initiation zones,
- Effect of damping on stress reduction,
- Influence of foundation geometry on stress distribution.

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IV. RESULTS AND DISCUSSION

4.1 Frequency Response of Directional Deformation

The cuboid conventional concrete (CC) foundation exhibited the highest peak deformation amplitude near the excitation frequency due to its high stiffness but low damping capacity. Introduction of rubberized concrete (CRC) reduced the peak deformation, indicating effective vibration attenuation.

The trapezoidal conventional concrete (TC) foundation showed lower deformation compared to CC, attributed to improved stiffness and better load distribution due to the wider base. The trapezoidal rubberized concrete (TRC) foundation demonstrated the lowest deformation amplitude among all cases. The combined effect of enhanced damping and optimized geometry resulted in a smoother frequency response curve with suppressed resonance peaks.

Overall trend of peak deformation amplitude: CC > CRC > TC > TRC

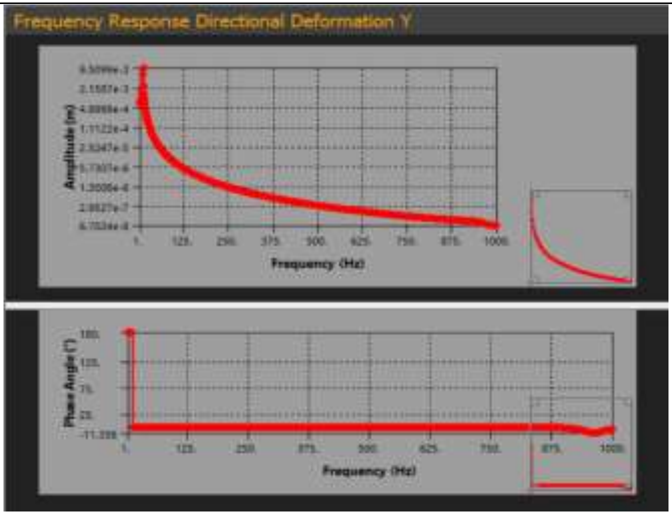
4.2 Frequency Response of Maximum Principal Stress

Dynamic stress response followed a similar trend. The CC foundation developed the highest maximum principal stress at frequencies close to excitation, indicating higher crack susceptibility under cyclic loading. Rubberized concrete foundations (CRC and TRC) showed reduced stress amplitudes due to energy dissipation and stress redistribution.

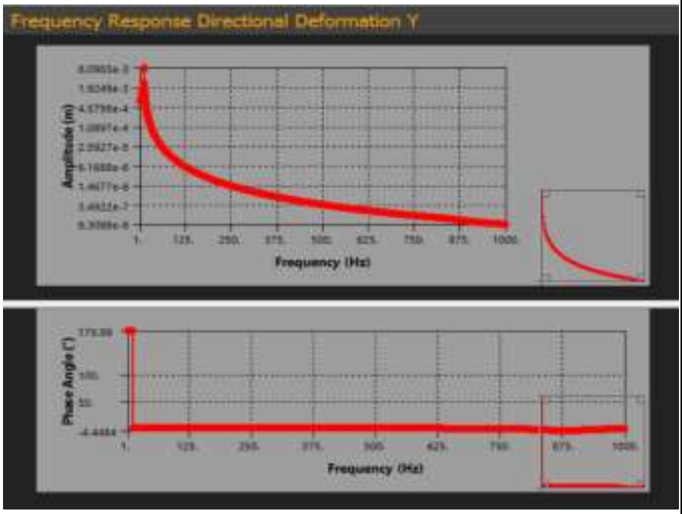
The trapezoidal geometry significantly reduced stress concentration at the base and side faces. The TRC foundation exhibited the lowest dynamic stress levels, demonstrating superior performance in terms of fatigue resistance and durability.

4.3 Effect of Material and Geometry

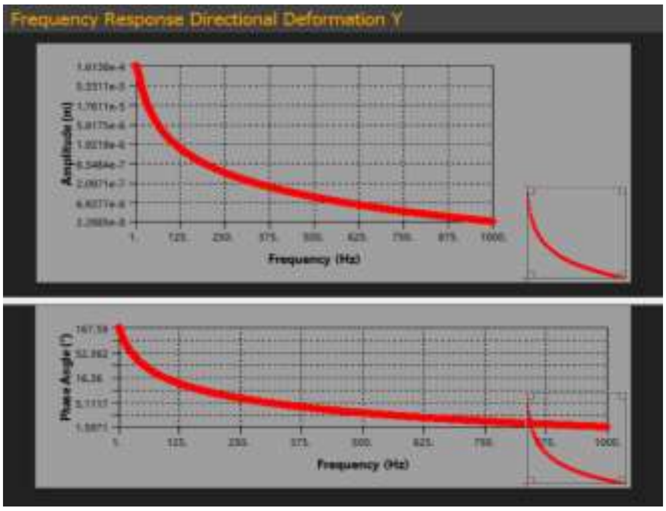
Rubberized concrete primarily influenced damping and reduced response amplitude, while trapezoidal geometry improved stiffness and stress distribution. The harmonic analysis clearly shows that material modification and geometric optimization act synergistically to improve vibration control.



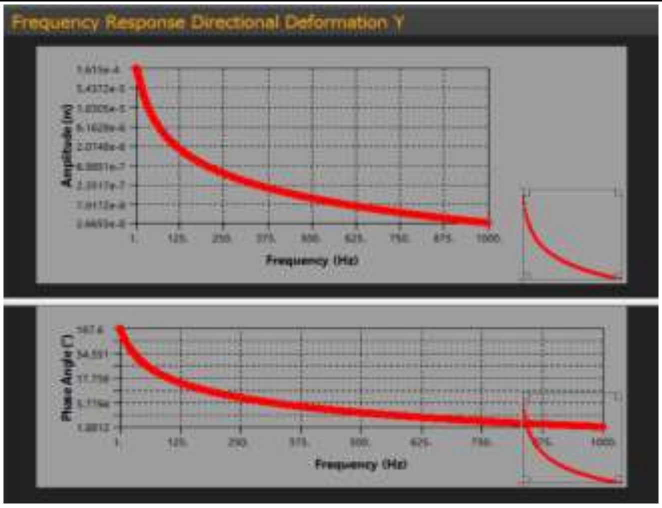
Graph 1: Frequency Response Directional Deformation Y of Cuboid Concrete



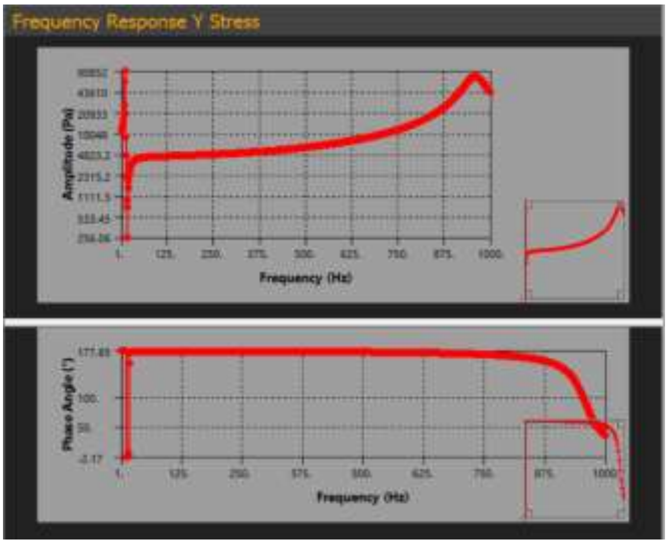
Graph 2: Frequency Response Directional Deformation Y of 10% Rubberized Cuboid Concrete



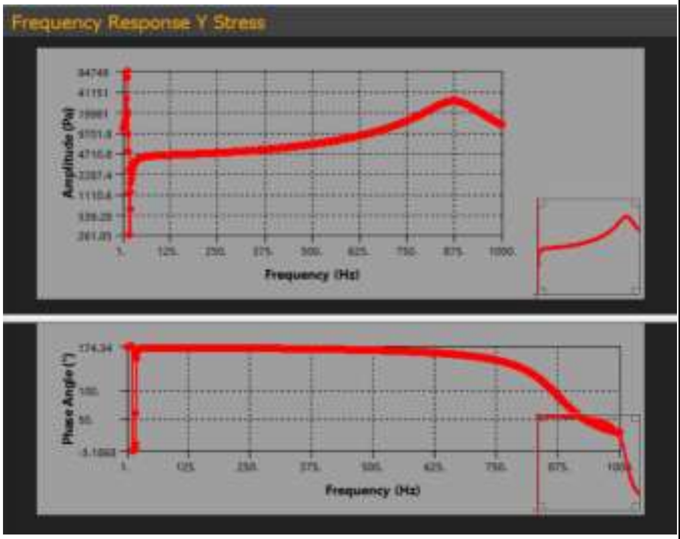
Graph 3: Frequency Response Directional Deformation Y of Trapezoidal Concrete



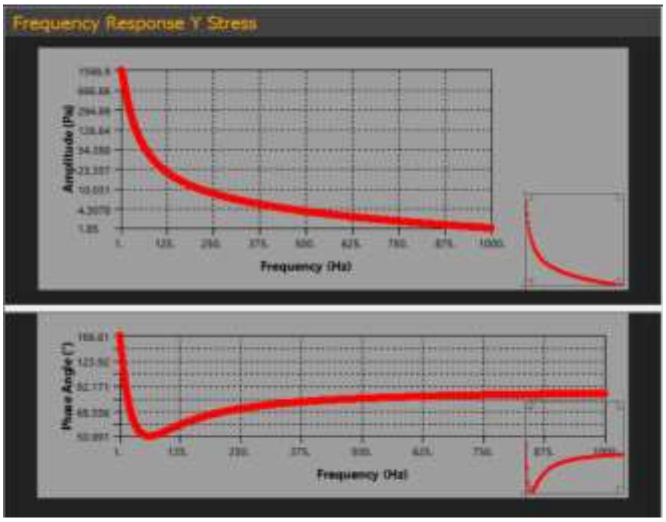
Graph 4: Frequency Response Directional Deformation Y of 10% Rubberized Trapezoidal Concrete



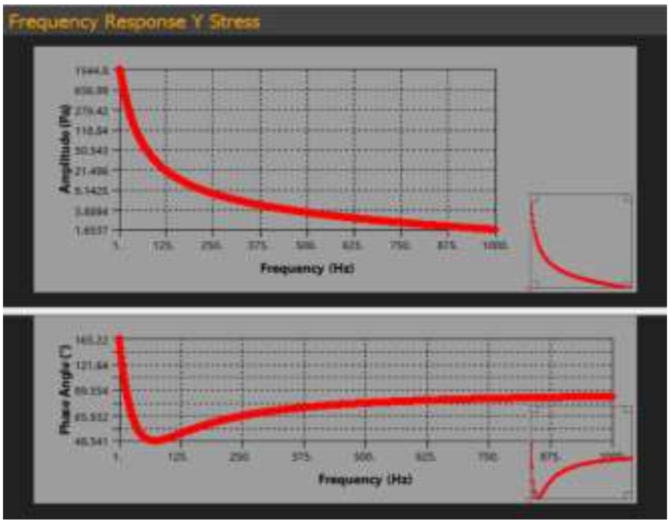
Graph 5: Frequency Response Stress Y of Cuboid Concrete



Graph 6: Frequency Response Stress Y of 10% Rubberized Cuboid Concrete



Graph 7: Frequency Response Stress Y of Trapezoidal Concrete



Graph 8: Frequency Response Stress Y of 10% Rubberized Trapezoidal Concrete

I. ACKNOWLEDGMENT

I would like to express my sincere gratitude to my project supervisor Dinesh Pandit Assistant Professor, Department of Civil Engineering, CSMSS Chhatrapati Sambhajinagar, for his continuous guidance, valuable suggestions, and constant encouragement throughout the course of this research work. His technical expertise and constructive feedback played a vital role in the successful completion of this study.

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