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Integration of Machine Learning in Dynamic Analysis of Rubber Based Block Type Machine Foundation

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ABSTRACT: As machinery evolves, designing foundations to handle dynamic loads has become more complex. This study compares two block-type machine foundation models—one with reinforced concrete and another with added polyurethane rubber for improved damping. Using STAAD.Pro, both were analyzed for static and dynamic loads at 3570 RPM. The rubber-based model showed better vibration absorption and flexibility. A machine learning model using Random Forest Classifier was developed in Python to predict foundation sustainability based on structural and vibration data. Results show that rubber integration reduces resonance risk, while AI enhances design efficiency and failure prediction.

KEYWORDS: STAAD. PRO, polyurethane rubber block, modal analysis, vibration analysis, stress contour, natural frequency, Random Forest Classifier, Python, sustainability check.

I. INTRODUCTION

For centuries, machines have played a crucial role in simplifying humans' life. As machinery continues to advance, the vibrations they produce have become a significant engineering challenge, making it essential to protect the machine's foundation and nearby structures. Previous researches have used many methods in analytically, experimentally and numerically to estimate the dynamic response of the machine foundations. Designing machine foundation is more complex than designing a regular static foundation. This is because, in addition to static loads on the floor of the machine, designers must consider the dynamic forces generated by the operation of the machine. This dynamic force is in turn transferred to the foundation that supporting the engine. A block type machine foundation is a type of foundation used to support heavy machinery and equipment, particularly in industrial settings. This foundation consists of a large, solid block of concrete that is designed to absorb and dissipate vibrations generated by the machinery. The natural frequency of the foundation system should be higher or lower than the operating frequency of the machine to avoid resonance effect preferable a separation of 50%. The rubber has been used as a part of many dampers and energy dissipater equipment due to its excellent energy absorbing properties. The use of rubber in geotechnical and earthquake engineering has been assessed by many researchers in many forms of sheets, grains, shredded etc. Polyurethane (PU) is a synthetic polymer made by combining polyols (a type of alcohol compounds) with diisocyanates (a type of isocyanate). PU material is highly customizable, making it a popular choice for applications ranging from flexible foam cushioning to rigid sheets used in construction and automotive industries. Machine Learning (ML) is transforming civil engineering, particularly in the design and maintenance of machine foundations. ML enhances predictive analysis of soil-structure interactions, which is crucial for understanding stability and vibration control under dynamic loads. The Random Forest algorithm can be used to check the sustainability of machine foundations by analysing various factors like foundation dimensions, material properties, machine weight, RPM, soil conditions, and vibration responses. By training the model on past data, it can predict whether a foundation will remain stable under dynamic loads or if modifications are needed. STAAD.Pro is a powerful structural analysis and design software widely used by civil and structural engineers to create and assess the safety of various structures like buildings, bridges, towers, and more. Structural analysis in STAAD.Pro for a machine foundation involves evaluating the stresses, deflections, vibrations, and overall stability of the foundation under both static and dynamic loads. Modal analysis is a structural dynamics technique used to determine a system's natural frequencies, mode shapes, and damping characteristics. Vibration

analysis is the study of oscillatory motion in structures and mechanical systems to assess their dynamic behaviour under various load conditions. Visual Studio Code (VS Code) is a powerful and lightweight integrated development environment (IDE) that offers an efficient workflow for machine learning (ML) development with Python 3.12. With the Python extension, it provides IntelliSense for code completion, linting tools like pylint for clean coding, and seamless execution of scripts.

II. LITERATURE SURVEY

Hasan ahmed salman et.al, 2024 [1]: a famous machine learning model for grouping and prediction uses is a random forest. Decision trees are the base for random forest method, that creates multiple decision tree and collects their result for giving final prediction. A random subset of dataset is made use to train every tree, and the last forecast is calculated by the total of the results from all the trees. The capacity of random forest to deal with datasets that are unbalanced and variables with missing values is one of their main advantages. They also reduce the chance of arbitrary variable selection which is limitation of model of certain types. By training number of decision trees on different data subsets, random forests can minimize over lifting and improve their generalization on new data which in another merit of this technique.

Paweł zielonka et.al, 2023 [2]: in recent times, polyurethane (pu) has gained wide use across colourful diligence due to its outstanding parcels, similar as high mechanical strength, excellent bruise resistance, continuity, and inflexibility at low temperatures. One of its crucial advantages is its capability to be customized to meet specific conditions, making it largely protean for different operations. This study specifically investigates the rheological behaviour of a polyurethane elastomer classified as pur (rigid polyurethane). The primary ideal was to dissect stress relaxation under different strain situations. Also, the study proposes a modified kelvin – voigt model to describe the stress relaxation process. The results verified the model's effectiveness in describing stress relaxation across a range of distortions from 50 to 100.

K.y. desai et.al, 2022 [3]: the design of machine foundations under harmonious loads is extensively carried out using barkan's system, as recommended in is 2974. This study focuses on a parametric analysis of the dynamic gets of block-type machine foundations using barkan's system. The analysis considers three different machines operating at 150 rpm, 250 rpm, and rpm, along with six different soil conditions(a) medium, stiff, and hard complexion, and(b) loose, medium, and thick beach. Foundation sizes are optimized grounded based on soil conditions, and each case is anatomized using both the traditional method and the fem model in staad.pro. The findings indicate that as complexion transitions from medium to hard and beach from loose to thick, the needed foundation size decreases. Likewise, an increase in soil stiffness leads to a rise in the natural frequency of the machine- foundation- soil system while reducing foundation breadth.

Kavya r p et.al, 2022 [4]: this study focuses on the analysis and design of a block- type machine foundation grounded on standard cargo data generally used in power shops and the oil painting and gas assiduity. To streamline the process, functions for analysis and design have been developed using vba (visual basic for applications) in an excel macro workbook, enabling robotization and perfecting effectiveness. The advised disturbing frequency is 2.5 hz, with a vibration breadth of 94.02 μm . According to graphical data from the codebook, the response falls within the abb' limit, icing respectable comfort situations for labour force. Also, the foundation's crotchets remain within the admissible limit of 5 of its length in both directions. The study also includes the layout and detailing of the block- type machine foundation.

III. METHODOLOGY

Two machine foundations are designed using Staad pro upon completion of the model building in Staad pro , the structural analysis is completed first, for both models having their respective modal analysis executed alongside vibration analysis.

TABLE 1. PROJECT INFORMATION

Location	Bengaluru
Project type	Machine foundation
Grade of concrete	M30
Steel	HYSD 500
Soil type	Well graded sand
Safe/Allowable Bearing Capacity	260 kN/m ²
Rubber blocks	Polyurethane
Operating speed	3570rpm
Pressure on machine area (DL1)	12.24kN/m ²
Dead load of rubber (DL2)	3.48kN/m ²
Dynamic load (F ₀)	0.328kN/m ²
Machine model	Industrial centrifugal blower

Structural Analysis In STAAD.Pro:

Model 1 is designed with material property using concrete only, in which the dimension of the foundation is 6x2.8x0.6m. Model 2 is designed with material property using concrete and rubber in which the foundation dimension is 6x2.8x0.6m and rubber is provide with dimension of 5x1.36x0.2m at the middle.

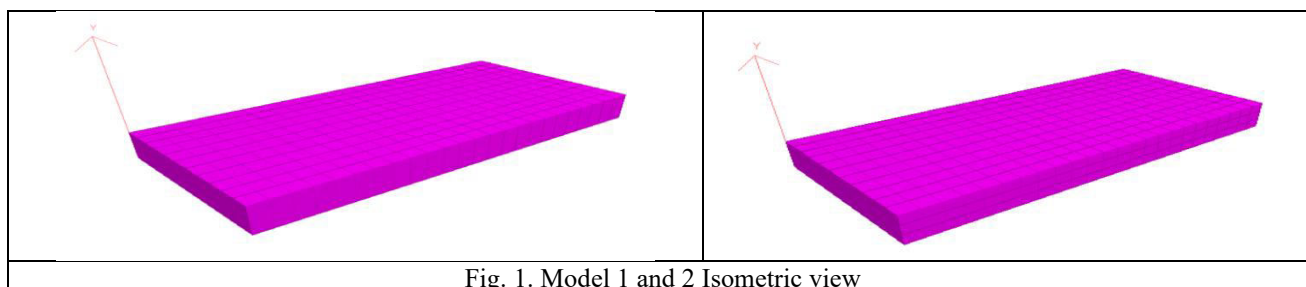


Fig. 1. Model 1 and 2 Isometric view

Modal and vibration analysis

Modal analysis is performed for both machine foundation (with and without rubber) to determine its natural frequency and model shapes, ensuring that dynamic characteristics of the structure are well separated from the operating frequency of 60Hz. Vibration analysis is performed for both machine foundation (with and without rubber) to determine its dynamic performance under operating conditions and ensure that the resulting displacement remain within the permissible limit.

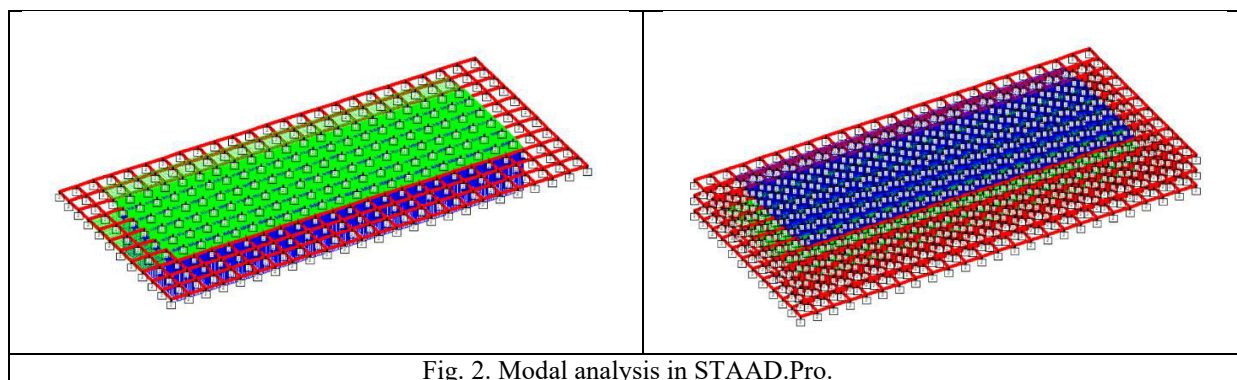


Fig. 2. Modal analysis in STAAD.Pro.

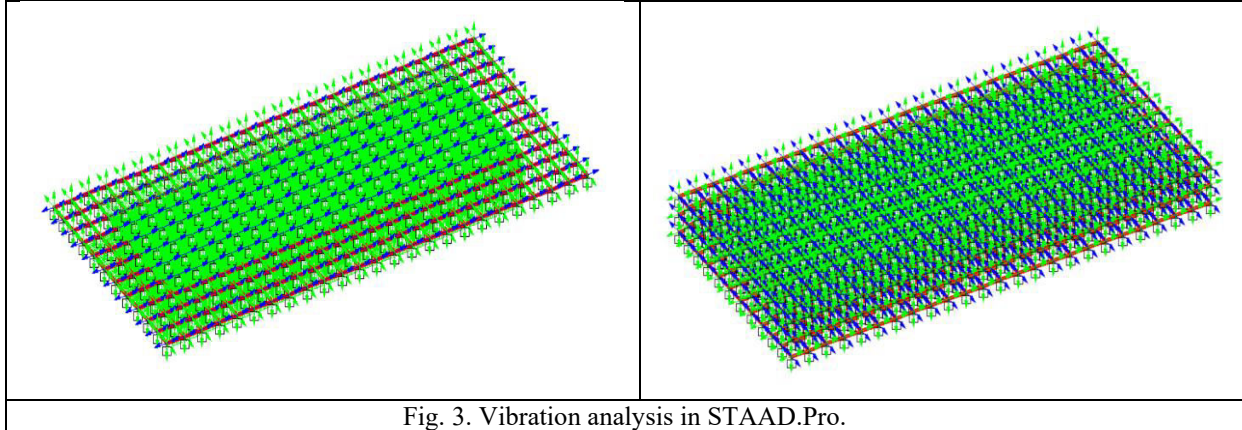


Fig. 3. Vibration analysis in STAAD.Pro.

Machine Learning Data

Machine Learning (ML) is a field within artificial intelligence (AI) that allows computers to recognise patterns from data and make predictions or decisions based on information without being explicitly programmed. The sustainability prediction model helps to determine whether a given set of condition will lead to sustainable outcome. It takes various inputs (like model number, load values, stress type) and predicts either sustainable or not sustainable. Model type: random forest classifier. We use random forest because it handles both numerical and categorical data well, provides reliable prediction, less prone to overfitting, gives feature importance information.

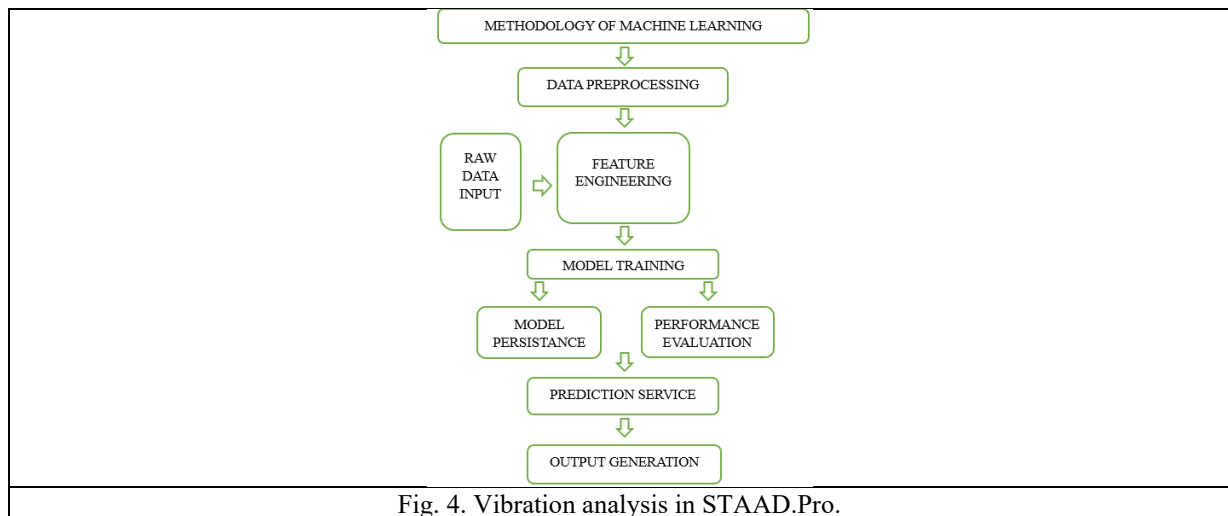


Fig. 4. Vibration analysis in STAAD.Pro.

IV. RESULTS AND DISCUSSION

STRUCTURAL ANALYSIS

In model-1 the sbc of 33.512 kn/m² is lower than the required 260 kn/m², which indicates that the existing soil has limited load bearing capacity. In model-2 the sbc of 24.440 kn/m² is lower than the required 260 kn/m², which indicates that inclusion of rubber layer effects the load distribution and soil interaction resulting in increased flexibility. In model-1 stress values is lower at the top and bottom of the machine foundation, which indicates more uniform load distribution. The structure is higher stiffness and rigidity which leads to reduced deformation under machine loads. In model-2 stress values at the top and bottom of the machine foundation is increasing especially at the bottom layer. It suggests that rubber absorb more load but also result in higher stress level.

SL NO.	STRESS TYPE	MAX TOP (kN/m ²)	MIN TOP (kN/m ²)	MAX BOTTOM (kN/m ²)	MIN BOTTOM (kN/m ²)	SL NO.	STRESS TYPE	MAX TOP (kN/m ²)	MIN TOP (kN/m ²)	MAX BOTTOM (kN/m ²)	MIN BOTTOM (kN/m ²)
1.	CASE 1	58.3	48.1	-0.809	-1.71	1.	CASE 1	98.9	48.4	91.3	23
2.	CASE 2	10.7	8.8	-0.148	-0.313	2.	CASE 2	540	264	91.3	23
3.	CASE 3	10.7	8.8	-0.148	-0.313	3.	CASE 3	79.1	38.7	73.1	18.4
4.	CASE 4	81.6	67.3	-1.13	-2.39	4.	CASE 4	324	159	54.8	13.8

Fig. 5. Model 1 and 2 stress values

Check For Deflection and Soil Pressure

In model-1, the model analysis reveals that natural frequency ranges from 17.981 Hz, 18.708 Hz, 19.941 Hz, 53.689 Hz and 72.985 Hz. it suggests that the dynamic response occur in this direction. In model-2, which induces a rubber layer, the modal analysis shows natural frequency ranging from 24.523 Hz, 32.305 Hz, 33.180 Hz, 34.059 Hz, 35.255 Hz and 35.940 Hz. The operating frequency is 60Hz so it is safe from resonance. The presence of rubber layer helps in damping out high frequency vibration, enhancing the overall stability of the foundation system. In the vibration analysis of model-1, the maximum vertical displacement is 1.924mm at node 113. In the vibration analysis of model-2, slightly higher vertical displacement, with the maximum value of 2.772mm at node 2. It suggests that rubber layer develop more flexibility into the system.

Mode	Frequency Hz	Period seconds	Participation X %	Participation Y %	Participation Z %	Type	Mode	Frequency Hz	Period seconds	Participation X %	Participation Y %	Participation Z %	Type
1	17.981	0.056	0.000	99.990	0.000	Elastic	1	24.523	0.041	0.000	44.932	0.000	Elastic
2	18.708	0.053	0.000	0.000	0.000	Elastic	2	32.305	0.031	0.000	2.924	0.000	Elastic
3	19.941	0.050	0.000	0.000	0.000	Elastic	3	33.180	0.030	0.000	26.734	0.000	Elastic
4	53.688	0.019	0.000	0.010	0.000	Elastic	4	34.059	0.029	0.000	0.000	0.000	Elastic
5	72.985	0.014	0.000	0.000	0.000	Elastic	5	35.255	0.028	0.000	0.000	0.000	Elastic
							6	35.940	0.028	0.000	13.243	0.000	Elastic

Fig. 6. Modal analysis of model 1 and 2

Mode	Frequency Hz	Period Seconds	Participation x %	Participation Y %	Participation Z %	Type
1	17.072	0.059	99.895	0.000	0.000	Elastic
2	17.132	0.058	0.000	0.000	99.946	Elastic
3	27.381	0.037	0.000	0.000	0.000	Elastic
4	30.076	0.033	0.000	89.731	0.000	Elastic
5	65.110	0.015	0.000	0.000	0.030	Elastic
6	66.000	0.015	0.080	0.000	0.000	Elastic

			Horizontal	Vertical	Horizontal	Resultant	Rotational
	Node	L/C	X mm	Y mm	Z mm	mm	rX rad rY rad rZ rad
Max X	202	1 LOAD CASE 1	1.022	0.493	0.527	1.251	-0.000 -0.000 -0.000
Min X	379	1 LOAD CASE 1	0.000	0.000	0.000	0.000	0.000 0.000 0.000
Max Y	211	1 LOAD CASE 1	1.021	0.737	0.531	1.367	-0.000 -0.000 -0.000
Min Y	379	1 LOAD CASE 1	0.000	0.000	0.000	0.000	0.000 0.000 0.000
Max Z	330	1 LOAD CASE 1	1.016	0.624	0.532	1.306	0.000 0.000 0.000
Min Z	379	1 LOAD CASE 1	0.000	0.000	0.000	0.000	0.000 0.000 0.000
Max rX	5	1 LOAD CASE 1	0.963	0.066	0.489	1.082	0.000 -0.000 -0.000
Min rX	106	1 LOAD CASE 1	0.993	0.176	0.517	1.133	-0.000 -0.000 -0.000
Max rY	306	1 LOAD CASE 1	1.002	0.138	0.506	1.131	0.000 0.000 0.000
Min rY	108	1 LOAD CASE 1	1.006	0.123	0.505	1.132	-0.000 -0.000 -0.000
Max rZ	29	1 LOAD CASE 1	1.012	0.308	0.526	1.182	-0.000 -0.000 0.000
Min rZ	2	1 LOAD CASE 1	0.973	0.057	0.486	1.089	0.000 0.000 -0.001
Max Ra	211	1 LOAD CASE 1	1.021	0.737	0.531	1.367	-0.000 -0.000 -0.000

Fig. 7. Modal And Vibration Analysis

Sustainability Crack

The block type machine foundation proves to be sustainable, with performance ranging from 90.55% to 95.28% among all load combination. The model remains its structural integrity throughout the analysis. The block type machine foundation incorporating with rubber proves to be sustainable, with performance ranging from 80.31% to 98.48% among all load combination. The model remains its structural integrity throughout the analysis.

<p>Model [1-8]: 1 Load [5-50, step 5]: 10 Stress Type [1-5]: 2</p> <p>-----</p> <p>Max Top: 10.7 Min Top: 8.8 Max Bottom: 0.148 Min Bottom: 0.313</p> <p>-----</p> <p>Processing...</p> <p>Result: Status: ✓ Sustainable Confidence: 90.55%</p> <p>-----</p>	<p>Model [1-8]: 1 Load [5-50, step 5]: 10 Stress Type [1-5]: 3</p> <p>-----</p> <p>Max Top: 10.7 Min Top: 8.8 Max Bottom: 0.148 Min Bottom: 0.313</p> <p>-----</p> <p>Processing...</p> <p>Result: Status: ✓ Sustainable Confidence: 95.28%</p> <p>-----</p>
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Fig. 8. Model 1 Load case 2 and 3

<p>Model [1-8]: 2 Load [5-50, step 5]: 10 Stress Type [1-5]: 2</p> <p>-----</p> <p>Max Top: 540 Min Top: 264 Max Bottom: 91.3 Min Bottom: 23</p> <p>-----</p> <p>Processing...</p> <p>Result: Status: ✓ Sustainable Confidence: 80.31%</p> <p>-----</p>	<p>Model [1-8]: 2 Load [5-50, step 5]: 10 Stress Type [1-5]: 3</p> <p>-----</p> <p>Max Top: 79.1 Min Top: 38.7 Max Bottom: 73.1 Min Bottom: 18.4</p> <p>-----</p> <p>Processing...</p> <p>Result: Status: ✓ Sustainable Confidence: 98.48%</p> <p>-----</p>
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Fig. 9. Model 2 Load case 2 and 3

V. CONCLUSION

It is observed that the comparative analysis of two foundation models was carried out with the SBC and stress contour values to evaluate their stability for supporting high speed machinery. The SBC of model-2 is 24.440 kn/m² due to the inclusion of the rubber blocks which alter load distribution and increase the soil flexibility. The SBC considered here is 260 kn/m² and obtained SBC is 90.6% which is lower than the considered value. The stress contour values increased especially at the bottom which indicates rubber layer introduces higher stress concentration. The model-2 is better choice because it absorbs vibration, protecting both the machine and surroundings. After modal analysis we observed that the natural frequency of model-2 ranging 24.523 Hz, 32.305 Hz, 33.180 Hz, 34.059 Hz, 35.255 Hz and 35.940 Hz, which is very lesser than critical resonance range. So, it is safe from resonance due to the inclusion of the rubber block which increase flexibility of machine foundation. Since observed frequency is 41.7% less than machine frequency model 2 performs better. It provides better vibration absorption and lower risk of resonance, making it safer for long term dynamic performance. After performing vibration analysis, it is noticed that maximum vertical vibration of model-2 is 2.772mm which is within permissible limit of 3mm. since the obtained value is 7.6% less than permissible limit there is no risk of tilting or overturning of the structure. Rubber increases energy dissipation and reduce transmission of dynamic loads to the machine foundation and its surroundings. From sustainability check of both the models under

various load combinations Model-1, consistently maintained a high sustainability range between 9.055% and 95.28% which indicates excellent stress distribution and minimal risk of failure under applied load and is very rigid and uniform stress behaviour. On other hand Model-2, shows sustainability ranges from 80.31% to 98.48%. Although its stress variation is slightly higher, it is good option for highspeed machines which operates with frequency of 60Hz. It has lower SBC and it protects both machine and surrounding structure from dynamic effects. Throughout the analysis, model-2 maintained structural integrity indication that composite foundation can achieve sustainability with functional performance in dynamic environment.

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