Review of massive turbine foundation: Misalignment analysis of a large tabletop foundation

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Abstract- The continuous manufacturing of more efficient turbines, together with stricter design and construction criteria for their onshore or offshore foundation structures, far exceeds the experience gained in the many disciplines. Soils with medium to high development potential are clays, whereas sandy soils have low to medium activity, low to medium sensitivity. That makes it ideal for embankment material. The risk of land subsidence owing to liquefaction during construction was assessed to be modest, with only two earthquakes generating liquefaction but not land subsidence. The natural frequency of the framed foundation structure (fn) should be compared to the engine operating frequency to determine the influence of turbine generator vibration on land subsidence (fo).

Index Terms- turbin foundation, tabletop foundation, misalignment, structural design, levalign equipment

I. Introduction

The continuing production of increasingly efficient turbines, along with increased criteria for the design and construction of their onshore or offshore foundation structures, greatly exceeds the accumulated experience obtained in the numerous disciplines concerned [1]. In addition to the above actions, the foundation structures of offshore turbines are also exposed to the sea condition and tides. Researchers in [1] summarizes the rules for estimating the hydrodynamic behavior and their interaction with the seabed-anchored foundation. For example, a foundation imperfections –one of them– is described as a permanent rotation of the foundation that is independent of the loading or is contingent on the permanent loading. This non-uniform subsoil deformations must be taken into account, especially in the case of cohesive soils, and are typically defined by a soil mechanics specialist [1].

Several aspect of design such a simplified modeling approach is also developed by [2] that incorporates the actual deformability properties of each layer of soil when calculating foundation displacements and pressures on the soil; that can eliminates mistakes in measuring the stiffness of the soils that interact with the foundation. He also compared the outcomes of the exact and estimated methods for calculating the depth of a sunken shaft.

The research concerning massive foundation structures are limited, contrary to the importance of their structures due to the overwhelming of loads, comparing to the other structures such tower, frame (beams, columns, walls and slabs) and also dome and bridge. This paper is amed to explore the development of their design, construction, materials, analysis and also the testing procedure of them.

II. LITERATURE REVIEW

A. Design of turbine foundation structures

The analysis and design of foundations and structures subjected to vibratory loads is considered a very complex problem because of the interaction of structural engineering, geotechnical engineering, mechanical engineering and the theory of vibration [3]. One of the more complicated issues that arise when constructing industrial structures is the design and construction of foundations for machines that generate huge dynamic loads, most notably compressors with crank-gear [4]. When determining the angle of tilt and pressure on the soil of a pile foundation, reference [5] said that is considered a conditional massive foundation pursuant to Art. 7.1 of SNiP II-B.5-67 and Appendix 22 of SN 200-62. He also stated that the magnitude of the moment from external loads at the level of the grillage's undersurface is used, which is incorrect as noted by several researcher [5]. The moment Ml of the force acting on the foundation's undersurface (plane AD) can be deemed equal to M only in the absence of an external horizontal load H. (see Fig. 1).

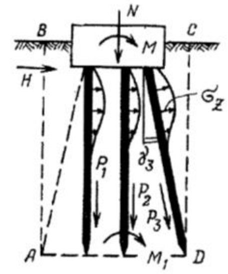

Fig. 1 Moment distribution along piles
Source: [5]

The engineer should be encouraged to employ finite element computer analysis techniques for mat foundation design by using the instructions offered in the study. The designer is intended to get significant insight into the practical and economical construction of large mat foundations by using finite element computer calculations [6].

The mass ratio is clearly inaccurate in describing system performance metrics such as amplitude, frequency, and velocity of vibration [7]. The finite element method enables for model calibration to account for system behavior. Calibration is usually done with accelerometers, sensitive transducers. It is possible to calculate deflections and stresses from accelerometer PSD plots. The deflections and stresses are compared by [7] to the calculated values.

The complete foundation design of dynamic equipment also explained by [8]. Unbalanced forces in rotating machines occur when the rotating part's mass centroid does not align with the rotation axis. Theoretically, rotating elements of machinery can be precisely balanced. In actuality, small mass eccentricities always remain. The eccentric rotating mass provides centrifugal forces proportional to machine speed. Machine wear, rotor play, and dirt collection all increase centrifugal forces over time [8].

B. Construction of turbine foundation

Reference [9] addresses concerns specific to TG foundations, such as building joints to allow repeated concrete pours, headed reinforcing to avoid rebar congestion, appropriate concrete mix to eliminate placement issues, and rebar modularization for ease of installation. Best practices are emphasized, and new ideas are explored to help decrease costs and speed up construction [9].

Also deal with shortcrete or grouting, when employing shotcrete effectively, logistics difficulties dominate. Maintaining a consistent mixture and spraying semi-continuously for hours is difficult [10]. The next section describes the difficulties and discusses remedies. Regarding mixing and placement, shotcrete must be able to be pumped from the delivery station to the placement position, often a distance of several thousand feet. As discussed previously, we will not repeat it here. To guarantee effective application from the nozzle to the wall, mixing is as critical as pumping technique [10].

A good explanation of design and construction of a reinforced concrete foundation block for a 200-megawatt turbo-generator also explored by [11].

C. Levalign expert equipment

A tool for leveling and flatness measurement that very often used by NDT operator is Levalign-Expert, that was a high-precision, high-power laser with an unambiguous spectrum of up to 100 meters (328 feet). The high-performance laser levels can be managed remotely with an app, ensuring the highest degree of accuracy for all geometric alignment tasks. It can be operated remotely by an interface which provides the highest level of precision for all geometric alignment operations. Engineer can placed self-leveling spinning laser Levalign-Expert equipment vertically or horizontally. Its revolving laser head is ideal for measuring the floor of a chamber, the foundations of test benches, or testing the flatness and plane parallelism of massive presses. It can measure flatness, straightness, parallelism, perpendicularity and level of flanges and foundations. Leveling of reference surfaces and base of circular and rectangular surface profiles can be done with one-man operation.

Fig. 2 Self-leveling spinning laser for flatness measurement Levalign-Expert using for this project
Source: [https://www.pruftechnik.com/]

Along with engineer technical reporting skills, powerful computing capabilities allow measurement analysis such as comparing any two surfaces, such as those in a press, or extending the measurement spectrum for larger surfaces. It is the ideal laser geometric instrument for engineers who provide comprehensive repair services in order to increase system availability and product efficiency.

As the internal excavation develops, ground anchors are set at the perimeter retaining wall. If the nearby land is private, wayleave is necessary. The main advantage of anchoring is the unencumbered construction space. Wall distortion is reduced using post-tensioned anchors. Load capacity may relax during permanent works construction, necessitating monitoring and re-stressing. The benefits of a clear excavation may be offset by anchor expenses. This is because the code requires high safety factors for temporary anchors [12]. And the design and construction of large massive turbine foundation basically can be found in reference [13-18]. While the materials used in these particular structures was described in [19-20].

Large diameter and deep drilled shafts necessitate extra care during construction. Excavation techniques differ from typical shaft drilling techniques due to size, depth, and subsurface conditions. Due to the high costs and dangers associated with development, geotechnical studies must address construction challenges. The installation of permanent steel liners as part of the foundation's structural design is encouraged [21].

Tolerances for erection and shipping are included in precast concrete design. The construction sequence must be designed. The connection designs for temporary and permanent members are distinct from those for cast-in-place concrete, which must account for additional shipping and lifting weights [22].

D. Treatment of mass concrete construction

The mass concrete maintenance plan should include temperature measurement and moisturizing maintenance. Special treatment should maintain mass concrete to minimize anomalous shrinkage, cracking, and damage [23].

The maintenance method is regenerative. Within 12 hours of pouring, a plastic film and a thermal insulation quilt are used to keep the concrete moist. The thin film is removed when the temperature differential between the inside and outside is less than 25°C. To manage the temperature difference between inside and outside concrete, use water mist mode cooling. Field employees should monitor aggregate and sand moisture content, modify mixing water content, and ensure concrete quality satisfies construction requirements. Winter construction requires good insulation. The maintenance process should be observed on the test axis at a vertical distance of 600 mm. The concrete's temperature should be managed. Continuous observation is required to ensure reasonable maintenance and reduce the effects of temperature stress [23].

For large-scale building projects, when failure has serious consequences, the authors advocate using the observational approach selectively rather than globally, and only when the following requirements are met: (1) The method's benefits and savings vastly outweigh the hazards; (2) Risk-related impairments are largely reparable and reversible; (3) Design and subcontractor integration [24].

The determintion of the contact pressure against a large raft foundation also examined by [25].

E. Dynamic assessment and pile configuration

A comprehensive design according several codes were researched by [28], while the dynamic analysis were proposed by [26-27, 20-32].

Reference [33] stated that for any pile raft configuration, as pile spacing increases, average settlement decreases and the effect is marginal beyond 6 m pile spacing, whereas differential settlement, maximum bending moment, and maximum shear force varied inconsistently; additionally, the load-sharing ratio gradually increases and the rate of increase is marginal beyond 6 m pile spacing; further, the load-sharing ratio gradually increases and the rate of increase is marginal beyond 6 m pile spacing.

The average settlement, load-sharing ratio, and maximum shear force are all largest in varied soil profiles, whereas the maximum bending moment is largest in homogeneous soil profiles [33].

The soil and structure interaction also studied by [34] and [35]. The effective input motion of the foundation in a soil–structure–equipment interaction model is always greater than the effective input motion in a fixed base model. The foundation effective input motion can be magnified 35.5 % larger than those of a fixed base model, especially for lower equipment–structure frequency ratio, $\xi\omega$. Thus, a fixed base model cannot accurately capture the structure–equipment system's effective input motion [34].

Reference [35] shows there are key metrics that indicate the dynamic dynamics of the soil–structure–equipment interaction system. The results demonstrate that when the equipment-structure frequency ratio ($\xi\omega$) is between 0.5 and 1.0, the peak of the equipment relative response has a different trend, indicating that dynamic characteristics of the structure–equipment system vary significantly.

Their research offers a parameter (Ψ) to assess equipment involvement in soil–structure interactions. The parameter is used to explain the variation of floor and equipment relative response with equipment-structure frequency ($\xi\omega$) and mass (ξm) [36].

F. Crack problems and their maintenance

Temperature variations create early-age cracks in huge mat foundations [37]. Drying and autogenous shrinkage are generally neglected when analyzing early-age cracking risk. Instead of employing a lot of reinforcement, change the proportions of the vast concrete mixture to lower strength and hydration heat.

The use of Portland cement with ground granulated blast-furnace slag reduces heat generation in concrete and reduces tensile strength by forming early-age cracks. Also lowering the temperature of fresh concrete during placing reduces thermal strains and cracking. In the analyzed mat foundation, early-age cracks were found to be related to the type and amount of cement, reinforcement design, and concrete cover. Injecting polyurethane resin into the structure's leaky seams worked well [37].

G. Loading tests and numerical analysis

Non-destructive load testing was studied by [38] for large scale foundation and also investigated by [39] and their numerical analysis.

They noticed that the field studies described in [38] contribute to a scant collection of large-scale shallow foundation tests on soft clay on extensively characterised sites. These studies serve as a critical benchmark for evaluating stiffness and strength parameter derivation methodologies and procedures, available constitutive models, and current prediction methods for shallow foundation response. Field testing is an invaluable and persuasive approach of evaluating analytical and numerical methods for forecasting the response of shallow foundations [38].

Numerical modeling and study of lrge scale mat foundation loading test also performed by [39]. The load displacement results for the 7x9 and 3x1 pile groups were accurately predicted utilizing predictions from the FEM analysis of the soil tests and lateral loading experiments done prior to the soil testing, including the geometry of the unloading and reloading cycles. This has aided in the determination of the suitable test conditions. Following the experiments that enhanced the pile modeling, an analysis was conducted that was able to reproduce the behavior of the 7x9 pile group after yielding to a certain amount [39].

III. CASE STUDY

A. Case study of an tabletop foundation

Based on the tabletop foundation calculation report, the structural geometry and its loading position of this structure can be depicted as in Fig 3 and Fig. 4 respectively.

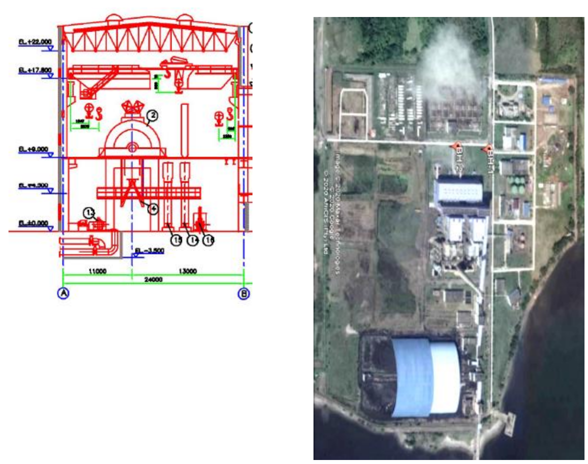

Fig. 3 Geometry and layout of tabletop foundation Turbine-1

基础负荷分配表
LOAD LIST OF PEDESTAL

荷载符号 LOAD NAME	垂直负荷(KN) VERTICAL LOAD	动荷载(KN) DYNAMICAL LOAD	扭矩力(KN) TORSIONAL FORCE	转子重(KN) ROTOR LOAD
P1	420	1100		85.04
P2	40			
P3	40			
P4	50			
P5	50			
P6	270		70	
P7	270		70	
P8	250	2100		176.37
P9	300			
P10	300			
P11	300			
P12	300			
P13	400		20	
P14	400		20	
P15	350	800		143.6
P16	165			193.36
P17	646			
P18	216			193.28
P19	19			

发电机短路力矩：4634KN.m
SHORT CIRCUIT MONENT: 4634KN.m

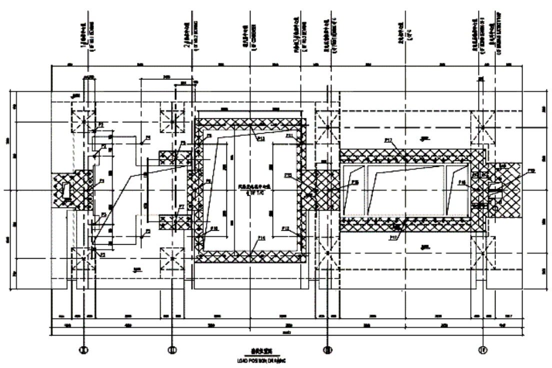

Fig. 4 Load position of tabletop foundation Turbine-1

While the pile layout of the tabletop foundation can be drawn as Fig.5.

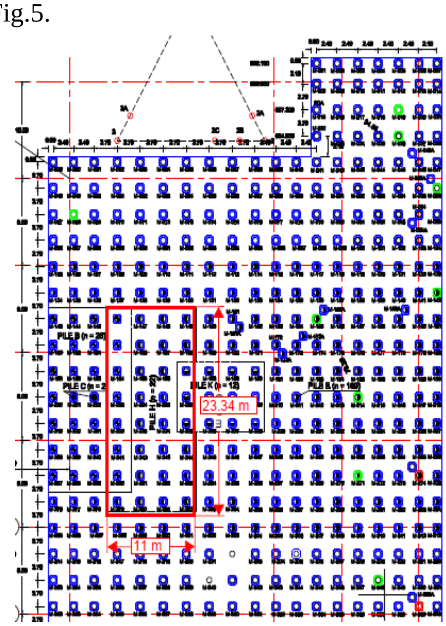

Fig. 5 Pile layout of tabletop foundation Turbine-1

B. Structural material assessment

Structural material especially concrete structures can be stated as follows:

1). Based on visual observations made in the field, it appears that the column is still in good condition; there is no damage to the column structural elements that would result in a reduction of the structural elements' strength. The column appears massive, and the absence of concrete shards implies that the structural elements have undergone relatively little deformation.

2). The Schmidt hammer test revealed that the concrete's quality was quite homogeneous, with a coefficient of variation of 5.93 %. This number is less than the ACI 214R-02 requirement (Evaluation of Strength Test Results of Concrete). Due to the relatively homogenous concrete used in the supporting column structure, differential deformation due to shrinkage or creep can be minimized.

3). The UPV test findings indicate that the state of the concrete in the majority of the tested column elements is satisfactory, with a concrete quality value ranging between 25 and 38 MPa, putting it in the category of medium to high strength concrete. A high density value in the concrete structure supporting the supporting column can help to decrease the risk of differential deformation due to shrinkage or creep.

C. Leveling measurement

Due to the lack of comparable data from prior measurements of decks and foundations, leveling measures cannot determine whether there has been a decline in the support column structure. The following conclusions can be drawn from the measurement and analysis results:

1) Elevation measurements for bearings 5 and 1 indicate a rising tendency of up to 0.949 mm/year for bearing 5. Bearing 2 is descending at a rate of -0.401 mm/year. While bearings 3 and 4 remained constant because they were used as zero reference points from the start of the experiment.

2) The datum point's elevation fluctuates between -2.04 mm and 1.20 mm in relation to point C2. Leveling deck relative to point C2 is plotted as:

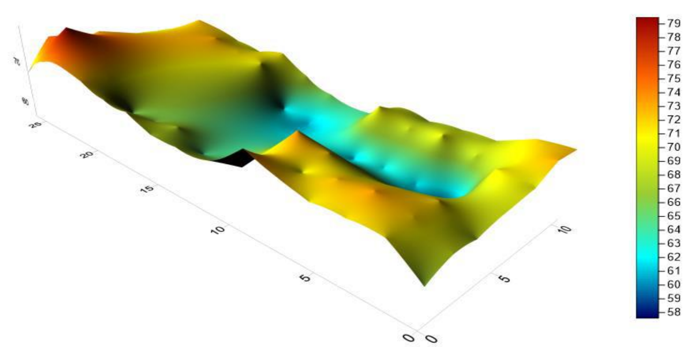

Fig. 6 Leveling deck relative to point C2

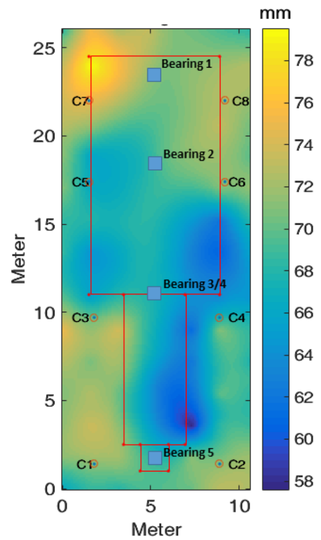

Fig. 7 2D Leveling deck from top

3) The foundation pier of turbine-generator deck unit-1 exhibits an outward slope of 1.6 cm, 4.1 cm, and 3 cm for piers C1, C2, and C7, respectively, whereas the C3 and C5 piles exhibit an inward slope of 1.7 cm and 0.8cm. The following Fig.8 depicts the verticality check's slope:

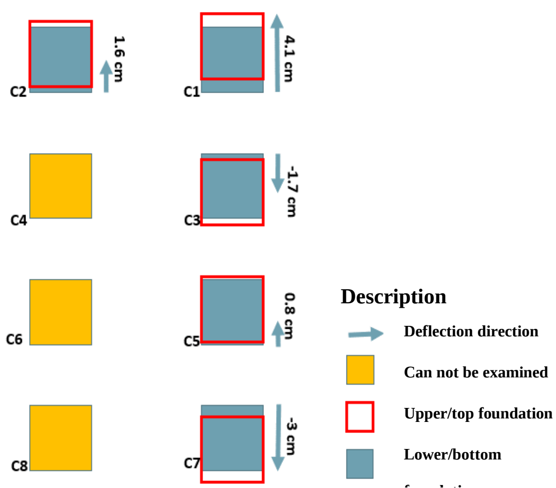

Fig. 8 Verticality check on foundation slope and tilting

4) Each supporting column has a slope of less than 1%.
5) There is not clear that the foundation and support column suffer from settlement, given there is no prior comparison data

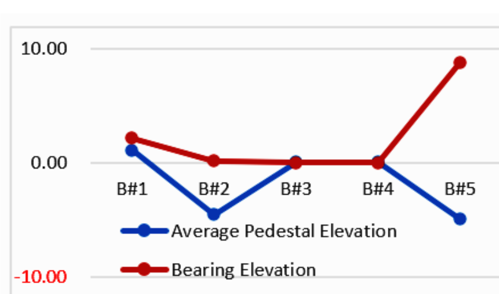

Fig. 9 Bearing and average pedestal elevation

D. Misalignment in tabletop foundation

The structural foundation type of the turbine generator I of HEPP (hydroelectric power plant) Labuhan Angin's support system is tabletop or framed foundation. At the moment, the turbine generator I HEPP is unable to operate; this is likely to be owing to a misalignment, as the Levalign Report indicates. The following diagram illustrates the bearing elevation based on design and the average pedestal height based on Levalign equipment such depicted in Fig. 9.

E. Several causes of misalignment

As illustrated in the fishbone diagram, there are various probable causes of misalignment can be depicted in Fig. 10.

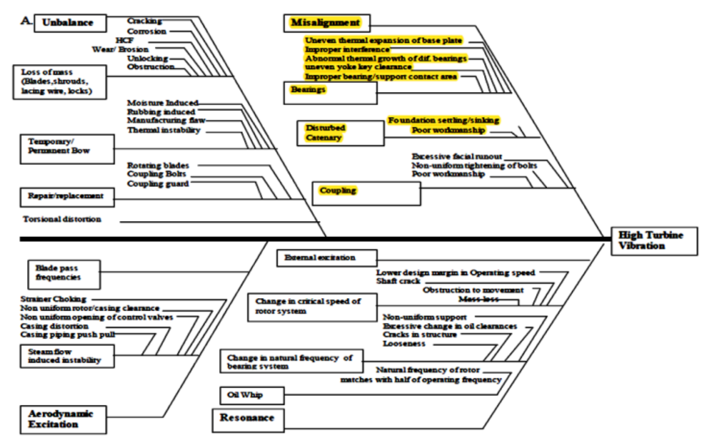

Fig. 10 Fish bone diagram of turbine vibration problems-I

The fishbone figure above identifies several possible causes of misalignment, including the following: a) Bearing • Uneven thermal expansion of base plate • Improper interference • Abnormal thermal development of differential bearings • Uneven yoke key clearance • Improper bearing/support contact area

And the second possibilities is b) Damaged Catenary that caused by foundation settlement or sinking.

F. Leveling problem solving

The suggestion regarding the leveling problems:

1) It is important to restore the turbine-generator foundation level to its original state in order to adequately support the engine above it.
2) It is vital to periodically measuring and monitoring significant elevations on the turbine and generator support structures in relation to fixed reference points.
3) The inspection of the turbine engine and generator's mechanical structure is required for defects that could result in bearing elevation changes.

IV. Conclusion

In general, the depositional environment at PLTU Labuhan up to 100 meters below ground level is a transitional environment influenced by the marine and terrestrial environments, ranging from sea fan deposits to marsh, which is classified into five groups: subtidal I, intertidal I, supratidal I, intertidal II, and supratidal II, with artificial embankment material at the top. In general, sandy soils have a high nitrogen content and are classified as medium to highly thick as depth increases. Meanwhile, clay soils normally range in consistency from stiff to hard, with the exception of the intratidal group II, which is often solid and deposited in a mud flat environment. At the site location, typical sandy soils have a medium to extremely dense relative density, whereas clay soils have a normal - active activity, a low to medium sensitivity, and a medium - very high development potential. It has a low activity, sensitivity, and development potential, which makes it ideal for embankment material.

The possibility for geological hazards produced by earthquakes, such as liquefaction, is limited, as fresh liquefaction can occur when the limitations of 0.346 g for BH-1 and 0.2679 g for BH-2 are exceeded.

A evaluation of the possibility for land subsidence induced by seismic elements determined that the risk of land subsidence due to liquefaction during the building's construction was low, with only two earthquakes reaching a critical level causing liquefaction but not land subsidence.

V. Suggestion

It is important to undertake a research to determine the influence of turbine generator vibration on the likelihood of land subsidence, among other things, by comparing the natural frequency of the framed foundation structure (fn) to the engine operating frequency (fo).

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