Static and Dynamic Analysis of Concrete Turbine Foundations

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Summary

The paper presents a systematic overview of the static and dynamic analysis of turbine foundations made of reinforced concrete. It discusses the load cases to be applied, the required ultimate limit and serviceability limit state checks, the assessment of the static and dynamic foundation stiffness and special provisions required in seismic areas. Turbine foundation design is an ambitious task, requiring attention to detail and plausibility checking of all input/output parameters, as a shut down of a turbine caused by an insufficiently designed and built foundation will lead to damage that is in no proportion to its cost.

Keywords: turbine foundation; block foundation; table foundation; spring support; structural dynamics; vibration amplitude; vibration velocity; misalignment matrix.

Introduction

During the first half of the twentieth century, engineering of turbine foundations was limited to a static analysis based on dead loads plus an additional, arbitrary vibration charge amounting to 3 to 5 times of the machine weight acting as a vertical, equivalent static load.

In 1955, the publication of the first edition of DIN 4024 provided for the first time rules for a standardised static and dynamic analysis. Although it was obvious that the calculation of the first order natural frequency alone was not sufficient to characterise the dynamic behaviour of turbine foundations, it needed the development of computers to allow models and methods for the analysis of turbine foundations to provide a more precise assessment of the dynamic behaviour.

General Information about Turbines and their Foundations

The present paper deals, particularly, with foundations of gas and steam turbines coupled to a generator for power production. For gas turbines, typically block foundations are used (*Fig. 1*). For steam turbines, the condenser arrangement in the low pressure (LP) turbine area leads to different foundation designs. In most cases, the condenser sits below the LP turbine leading to a table-type foundation (*Fig. 2*), with two possible arrangements: either, the condenser is welded to the LP turbine nozzle with a smaller part of the condenser weight hanging at the LP turbine, and the remaining bigger part of the condenser dead load supported by springs, allowing heat expansion of the condenser downwards, or the condenser is fixed at the bottom with a bellow between condenser and LP turbine nozzle to allow heat expansion upwards. In this case, neither dead load nor heat expansion will be part of the foundation analysis, but the vacuum pull will be an additional load case.

Block and table foundations may be placed directly on the ground or may be supported by piles, if only a deeper layer of soil has sufficient load-bearing capacity. These foundations should be separated from the surrounding structure by a joint filled with an elastic material.

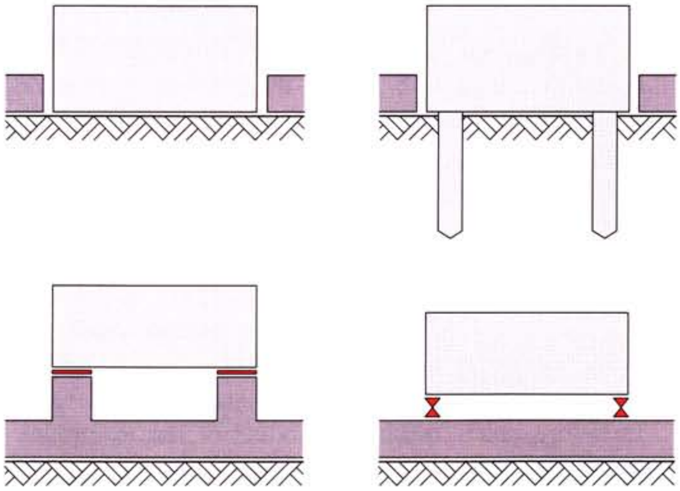

Fig. 1: Bedding types of a block foundation[2]

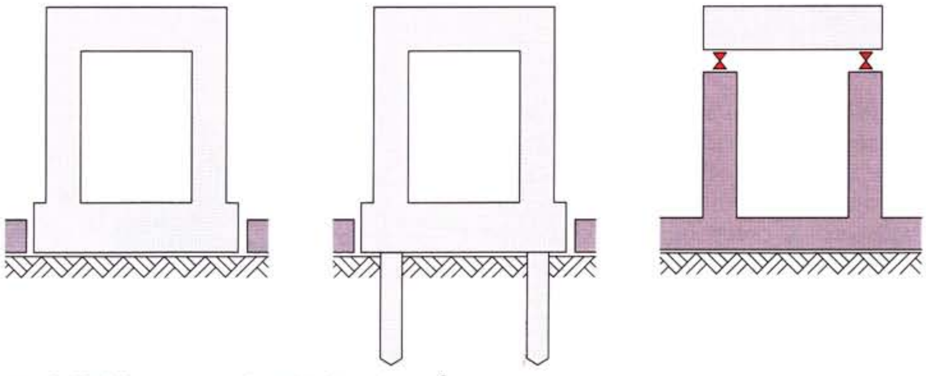

Fig. 2: Bedding types of a table foundation[2]

Vibration-controlled spring-supported block foundations may simply be placed on the floor while in case of table foundations such spring elements are arranged below the table top. The actual turbine foundation is then reduced to the spring-supported top part while the substructure can be completely neglected in the dynamic analysis of the spring-supported part because of the high vibration control effect of the springs.

Design methods for turbine foundations have developed gradually over time from rule-of-thumb to scientific engineering methods. Usually, the preliminary foundation size (determined by mass, shape and thickness) is decided by applying simple design rules. The concept is that vibrations are attenuated and absorbed by the foundation block that behaves as a rigid body on the supporting material. The foundation weight in the case of rotating machines should be at least 3 times the total machine weight. For block foundations on piles or springs this ratio can be reduced to 2,5 times.[1]

The dimensions of table foundations depend also on the limits of the static and dynamic foundation deformation during operation. The intention of the machine manufacturers to increase the efficiency of the turbine by reducing the distance between the turbine blade tips and the casing leads to high sensitivity of these aspects.

Although in many cases the machines are similar or even identical, different soil and site conditions, for example, seismic requirements prevent standardising of their foundations. In addition, authorities, the investor, the operator or the machine manufacturers may have different interests leading to different requirements in each single case. Therefore, each turbine foundation is a unique system that has to be designed and analysed separately in every single detail.

Load Cases

In the foundation analysis, site-specific environmental loads such as wind and snow in case of outdoor installations, seismic loads and material-specific loads such as creep and shrinking have to be taken into account. Most important is the adequate consideration of machine-specific loads that are provided by the machine manufacturers. These loads are divided into the following:

- Static and dynamic loads.
- Loads during operation.
- Loads during an emergency case.

Main static loads are as follows:

- Loads during machine installation including that of auxiliary equipment and lifting gear.
- Dead load of the equipment.
- Moments caused by the driving mechanism typically given as an equivalent vertical load couple. The magnitude of this torque load depends on the rotational speed and power output.
- Condenser loads in case of steam turbines either as dead load if the condenser is welded to the turbine nozzle or as vacuum load in case of an elastic bellow between condenser and turbine nozzle.
- Friction loads in the bearing areas, resulting from thermal expansion of the machines and their casings. Such loads are given as maximum values for support locations, and collectively do not impose a net resultant force on the foundation, but they must be considered in the design of the aforementioned support locations.
- Piping loads.
- Loads caused by varying temperatures of the machines.

Main dynamic loads during operation are caused by unbalance (created when the mass centroid of the rotating part does not coincide with the centre of rotation) with a frequency corresponding to machine speed. These loads are typically given by the machine manufacturer. If not, they may be calculated via the balance quality grade of the rotor.

The balance quality grade G is the product of the maximum permissible eccentricity e (mm) and the maximum angle velocity of the rotor ω (rad/s), as illustrated in *Fig. 3*. In industry, balance quality grades are usually determined in accordance with ISO 1940/1.[3] They are separated from each other by a factor of 2,5. For turbines and generators, the intended balance quality grade is usually G = 2,5 mm/s. The resultant unbalanced load $F(t)$ (N) is calculated with the rotating mass m (kg) and the balance quality grade G (mm/s) as follows:

$$F(t) = m \cdot e \cdot \omega^2 \qquad (1)$$

When fixing the unbalanced load for the analysis, the increase of unbalance in the course of operation has to be taken into account. This can be done in two ways: either the balance quality grade is assumed to be one step worse (e.g. G = 6,3 instead of 2,5), or $F(t)$ according to Eq. (1) is multiplied with a factor, which should be typically >2, although not fixed by rules.

Main dynamic emergency loads are caused by the following:

- Increased unbalance due to, for example, blade damage or rotor bending. As a simplification, the emergency unbalance may be assumed to be 6 times the unbalance during normal operation.
- Short circuit in the generator, causing high anti-metric loads transmitted via casing as a vertical load couple into the foundation. As a simplification, the load case short circuit may be replaced by an equivalent static load. This may lead, however, to a very conservative foundation design. It is, therefore, possible and even preferable to use a time history of the short circuit moment (e.g. the excitation/time relationship) as given in DIN 4024, Part 1[4] for excitation in a dynamic analysis.
- Mis-synchronisation in the generator also causing high transient loads. However, these loads are typically assumed to be covered by the load case generator short circuit.

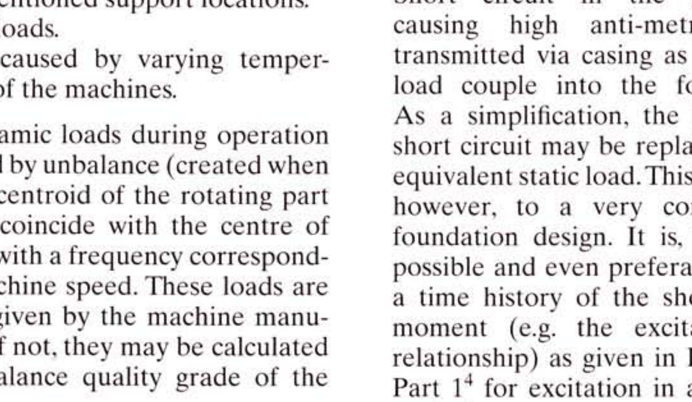

Fig. 3: Scheme of unbalance loads[2]

Ultimate Limit State Checks

Equivalent Static Loads

For foundations with simple geometry, the analysis may be eased by applying equivalent static loads, instead of making a full dynamic analysis.[4]

The equivalent static load, accounting for effects of the unbalanced load $F(t)$ can be calculated as follows:

$$F = \nu \cdot F(t) = \frac{1}{\left|1-\eta^2\right|} \cdot F(t),$$

$$\text{and } F_{\max} = 15 \cdot F(t) \tag{2}$$

where η is the ratio between operating frequency f_m and the nearest foundation natural frequency f_n:

$$\eta = \frac{f_m}{f_n} \tag{3}$$

In Eq. (2), the amplification factor ν is derived from the resonance curve of an undamped system with unbalanced excitation. Out of the resonance range, the resonance curves from undamped and damped systems are similar. Hence, for calculation, the analysis is based on the resonance curve of an undamped system by limiting the amplification factor ν (according to DIN 4024, Part 1 the limit for $\nu = 15$).

Adopting a conservative approach according to Ref. [4], the unbalanced load $F(t)$ to be used here has to be calculated for an emergency case in order to be on the safe side. It is assumed to be 6 times higher than that for normal operation, corresponding to $G = 6 \times 6{,}3 = 38$ mm/s (G38). When extracting $f_m/50$ it becomes possible to calculate the unbalanced loads $F(t)$ for different machine speeds:

$$F(t) = m \cdot e \cdot \omega^2 = 1{,}2 \cdot (m \cdot g) \cdot \frac{f_m}{50} \tag{4}$$

Simplistically, DIN 4024, Part 1[4] proposes that the equivalent static moment for the load case generator short circuit can be taken to be 1,7 times the highest value of the short circuit moment.

Calculation of Maximum Internal Forces

The stability of the system has to be proven for all static and dynamic load cases. Dynamic load cases and the rules for their superposition (partial safety and combination factors) are usually given by the machine manufacturer. Static load cases and the rules for their superposition are governed by local codes and regulations. However, experience shows that it must be checked if this superposition leads to maximum internal forces in each of the following situations, as such specific load conditions are not covered by ordinary codes and regulations:

- equipment installation;
- test cases;
- normal operation;
- emergency cases.

The reinforced concrete design shall be carried out for the envelope of the maximum internal forces, derived from above-mentioned load cases. The foundation shall be designed as a monolithic block without expansion or isolation joints.

Serviceability Limit State Checks

The serviceability limit state checks are often decisive in machine foundation design. Following checks need to be carried out, by using the same calculation model as for the ultimate limit state check:

- calculation and judgement of eigenmodes and eigenfrequencies;
- calculation and judgement of vibration amplitudes/velocities during operation;
- calculation and judgement of dynamic and static foundation stiffness.

Judgement of Eigenfrequencies

The judgement of the dynamic behaviour of a machine foundation can be done by comparing its eigenfrequencies, f_n, with the operation frequencies of the machine, f_m. According to Ref. [4], the first order natural frequency shall be at least 25% above or 20% below the operating frequency, and the higher order natural frequencies shall be at least ±10% above/below the operating frequency in order to avoid major resonance effects:

$$f_1 \leq 0{,}8 \cdot f_m \text{ respectively } f_1$$
$$f_1 \geq 1{,}25 \cdot f_m \tag{5}$$

$$f_n \leq 0{,}9 \cdot f_m \text{ respectively}$$
$$f_{n+1} \geq 1{,}1 \cdot f_m \tag{6}$$

This requirement is based on the fact that considering the resonance curve of an undamped system with unbalanced excitation, the amplification factor ν at/close to resonance is theoretically infinitely large, and hence the displacements cannot be controlled any more. In *Fig. 4*, the resonance curves for systems with different damping values (D = 0–1,5) are given. The practical conclusion is that by controlling the eigenfrequencies, so as to be higher or lower than the exciting frequency, the vibration displacements can be limited to permissible values.[4] The operating frequencies for turbines are generally 60 or 30 Hz and 50 or 25 Hz respectively. Considering calculation uncertainties (such as tolerances of the E-Modulus of concrete), in practice the frequency range of 20% above and below the operation frequency is investigated, whereby each eigenfrequency has to be assessed together with its eigenform. If eigenfrequencies are found within this range, an explicit calculation of the dynamic characteristics of the foundation becomes necessary.

Calculation of Vibration Displacements during Operation

As it is usually not possible to keep the above-mentioned frequency ranges

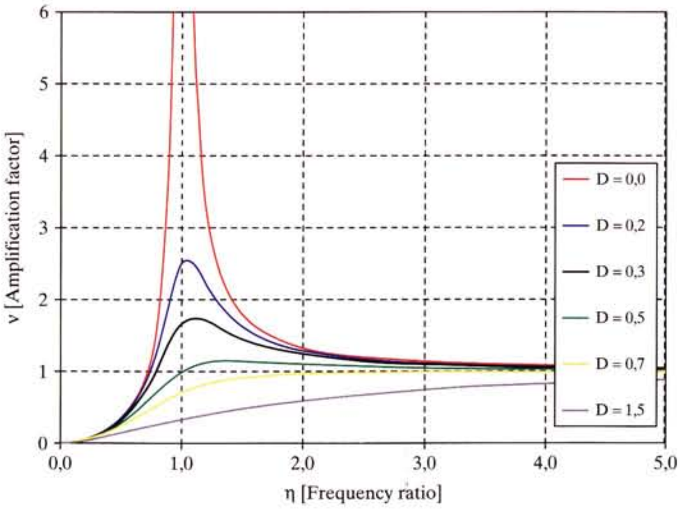

Fig. 4: Amplification factor ν for excitation by unbalances

free of resonances, an additional assessment of the foundation is required by calculating the following:

- vibration displacement s, in micrometres (zero to peak);
- vibration velocity v in millimetres per second.

For harmonic or sinusoidal vibrations consisting of several parts with different frequencies the r.m.s. (broad-band or root mean square) vibration velocity ($v_{\text{r.m.s.}}$ or v_{eff}) is the basis for the assessment.

The vibration velocity v_{eff} can be directly measured, but can also be derived from the peak velocity v:

$$v = \sqrt{2} \cdot v_{\text{eff}} \tag{7}$$

For harmonic vibration with the frequency f (Hz), the relation between the displacement s (μm) and the velocity v_{eff} (mm/s) is as follows:

$$s = 1000 \cdot \frac{\sqrt{2} \cdot v_{\text{eff}}}{2 \cdot \pi \cdot f} = \frac{450 \cdot v_{\text{eff}}}{2 \cdot f} \tag{8}$$

Vibration displacements during operation are calculated by a forced vibration analysis applying unbalanced loads at the bearing locations. If the unbalanced loads are given by the machine manufacturer, their derivation needs to be checked. If they are, for example, the maximum unbalanced load to be expected, the resulting situation would be close to the alarm or even shut down limit. These loads are therefore, not the right ones to calculate displacements during normal operation. If these maximum unbalanced loads are used, the system damping should be increased in order to get more realistic results.

Assessment of Vibration Displacements during Operation

The limits for permissible displacements during operation depend on the excitation frequency, lower rotor speeds permitting higher foundation amplitudes. If no information is available from the machine manufacturer, displacements may be assessed according to ISO 10816.[5–7] A comparison of generic limits as given in the codes and specific ones as requested from machine manufacturers shows major differences, while the specific ones are usually more stringent (*Fig. 5*).

According to ISO 10816, Part 2, displacements at normal operation of steam turbines should be less than 12,1 μm (r.m.s.) and peak amplitudes below 17,1 μm based on a balance quality grade *G* 2,5. Such low displacements cannot be expected if the rotating parts are poorly balanced. It needs to be considered that displacements may grow after a while because of an increasing unbalance caused by bearing wear and tear.

Displacements are always calculated for excitation in a single bearing. The superposition of the displacements resulting from the excitation in each single bearing can be done applying the square root of the sum of the squares (SRSS) procedure, as simply adding up the peak values would lead to highly conservative results. The SRSS method assumes that single maximum displacements are statistically independent, which is a valid assumption.

Dynamic Foundation Stiffness

An analysis wherein foundation and shaft are coupled is not common in civil engineering today. It is, however, necessary to calculate the dynamic stiffness at the bearing locations of the rotor for the design of the shaft and the calculation of the critical shaft speed. The machine manufacturer makes certain assumptions regarding the bearing locations for the design of the shaft where stiffness and damping of the oil film, the bearing itself and the foundation including its substructure are taken into account. This leads to certain requirements for the foundation. Quite often it is, however, sufficient to prove a certain requested minimal dynamic stiffness at the bearing locations. The dynamic stiffness is different compared to the static stiffness as inertia and the deformation behaviour of the foundation under harmonic dynamic loads is considered. The machine manufacturer may, for example, require a minimum dynamic stiffness at a bearing location of a steam turbine foundation of 4 kN/μm at a frequency of 50 Hz. In some cases, the shaft analysis will be repeated later taking the actual dynamic stiffness into account. While it is often thought that the dynamic stiffness of the elastically supported foundations is quite low, there is actually no major difference compared to conventional foundations in the important frequency range around the operational speed, as the stiffness depends mainly on inertia. *Figure 6* shows a typical diagram for the dynamic stiffness *versus* frequency for each bearing location (turbine and generator bearings) of a

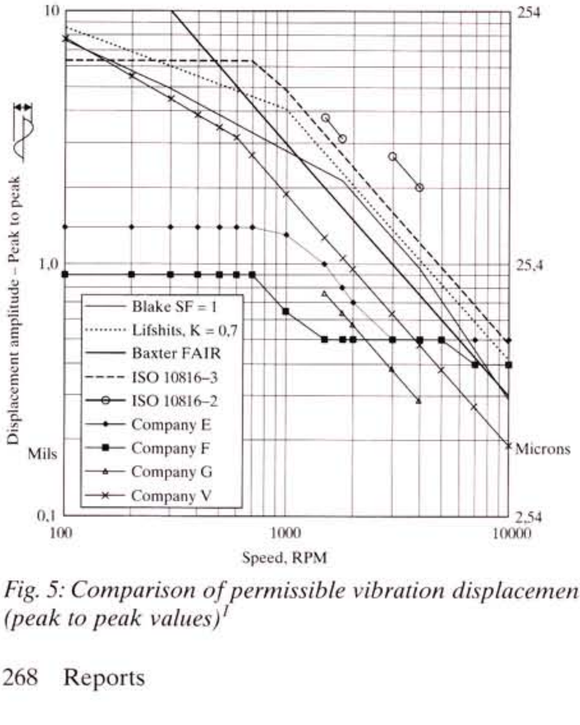

Fig. 5: Comparison of permissible vibration displacements (peak to peak values)[1]

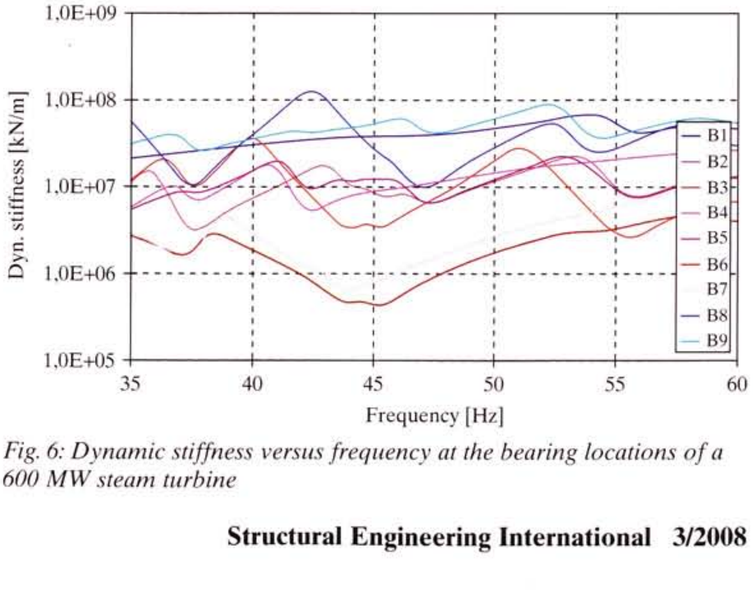

Fig. 6: Dynamic stiffness versus frequency at the bearing locations of a 600 MW steam turbine

spring-supported table foundation for a 600 MW steam turbine.

Static Foundation Stiffness

To prove a sufficient static stiffness it is not only necessary to compare the actual foundation deformation with the maximum permissible deformation but also the relative deformation at the different bearing locations, as the turbine foundation provides the stiffness for the different machine parts. Typically the machine manufacturer will provide deformation limits permissible after the alignment of the shaft, and load combinations for which these limits are valid (the so called "misalignment matrix"). This leads to a specific deformation analysis for the foundation. Of major interest is, for example, the difference between the deformation during operation and when the machine is shut down. The loads have to be combined in a most unfavourable constellation, where limits are given for shifts or torsion of the shaft line. In many cases, the permissible bearing pressure, the bearing pressure distribution or the permissible bending stresses in the shaft are important parameters.

Models and Calculation Methods

For concrete turbine foundations, a linear elastic analysis is usually sufficient, as amplitudes and static deformations are quite small. The stiffness change caused by cracks can be neglected in the analysis of new foundations.

The modelling of turbine foundations can be based on a three-dimensional (3D) beam system, a plate system, volume elements, a folded plate structure or combinations of these possibilities. Machine parts are modelled as single masses in their exact centre of gravity. For more accurate results (and being less conservative), mass inertia moments of machine parts can be taken into account. The connection between the machine parts and the foundation is typically done by rigid rods as the stiffness of casings and bearings is usually unknown. This procedure may lead to an unintentional or unrealistic stiffening of the foundation. One should be, therefore, very careful in using rigid connections. It may be preferable to check their influence in simplified models.

In general, beam models have been favoured for table foundations. This model is clear and has a less degree of freedom. It is usually sufficient to describe all major parameters. The same model can be used for the static and dynamic analysis. The beam system represents the actual load response of the longitudinal and lateral beams better than a volume element model. Owing to practical reasons, the reinforcement arrangement will be the same as that of a beam system. In addition, a higher stiffness is concentrated in the nodes of beam systems than when using volume elements. The nodal connection of machine parts, as described before, will lead, therefore, to fewer mistakes in the analysis.

For more massive block foundations the situation is different. There the volume elements have advantages, allowing better modelling of the concrete block. Typically the surface of the finite element (FE) model is directly generated from the computer aided design (CAD) layout. Using volume elements has, on the other hand, some disadvantages, such as machine parts are typically not available as a 3D model, and as their stiffness distribution is usually unknown, they are shown as mass elements connected with the concrete block. A connection via rigid rods is not possible in single locations for numerical reasons. The necessary cross-linking inside the volume model will, therefore, lead to local stiffening in the corresponding foundation areas. These influences depend on the selected net mesh. Further, the different degrees of freedom of volume and beam elements have to be considered as well as the stiffness steps at the nodes where the connection takes place.

Soil has a special importance in the analysis of turbine foundations. Typically, using the elastic and damping properties of the soil is sufficient in generating the model. The static and dynamic properties of the soil are represented by springs in the corresponding nodes. In some cases, it may be preferable to take the interaction between subsoil and turbine foundation in the analysis into account. The soil is shown in this case as a boundary element. The coupling with the structural model is done via a corresponding algorithm.[8]

Requirements in Seismic Areas

Stability and Serviceability

In areas where strong earthquakes are common, electrical energy is of prime importance for the so-called lifeline structures such as hospitals and power plants. Generally, the local codes and regulations provide certain requirements; but often the owner of the power plant will give detailed requirements for the availability of the power plant after an earthquake. These requirements may be as follows:

- Non-stop working of machines after an earthquake of medium strength and availability after one day in case of a strong earthquake, or
- no shut down even in case of the strongest possible earthquake.

These requirements have obviously to be quantified, where the site-specific seismic acceleration is of major importance. The machine manufacturer will give permissible machine accelerations, typically between 0,4 and 0,8 g. Possible damage may be for example:

- rotor damage when permissible shaft stresses are exceeded;
- bearing damage because of an excessive bearing pressure;
- rotor blades touching the casing;
- rupture of steam or other pipe work because of high relative displacements;
- collision of structural parts, for example deck and mezzanine floors.

In many cases, the limit of the permissible accelerations is reached quite fast, as in case of a typical table foundation. An amplification factor between accelerations on soil and deck level of 3 or 4 is quite common, so that a soil acceleration below 0,2 g may already lead to critical machine accelerations. The actual soil accelerations are, however, in many locations far above this figure, for example, in many southern European countries, Middle East, Japan or in western states of the United States. An elastic support of the deck may reduce the response acceleration of a table foundation. Low tuning and high damping are very effective as far as the response accelerations are concerned without increasing relative displacements too much.

The importance of the stability of the turbine house and the foundations is obvious. This includes special requirements in case of an earthquake. When using a standard design, stability is typically not a problem. Still, damage of the structure cannot be excluded in case of an earthquake because of a deliberate ductile design and stress shifts. This may directly or indirectly impair operation, for example, if subsequent

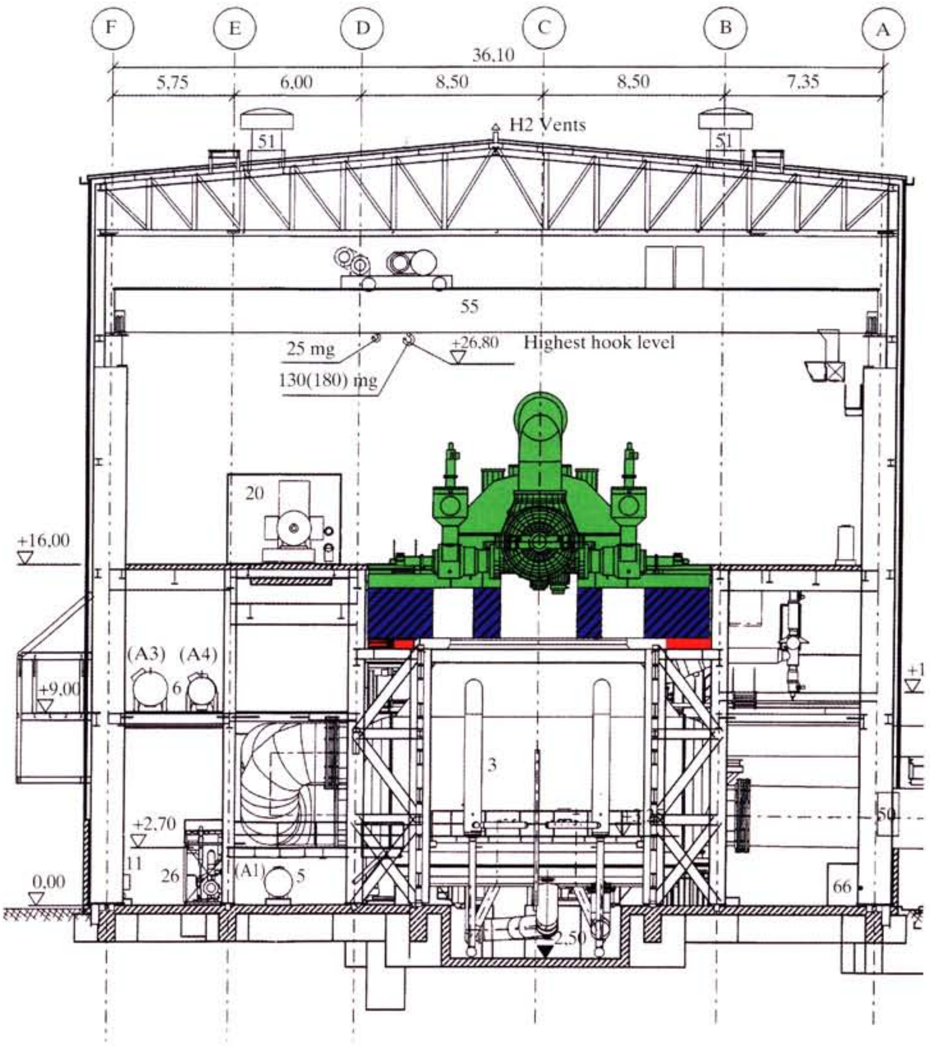

Fig. 7: Cross-section through a turbine building with integrated table foundation (Turkey)

measures for the repair of damage in the structure become necessary. An increase of safety on the input side simply by increasing the importance factor is usually not sufficient to guarantee a completely elastic behaviour of the structure. It is, therefore, recommended not to apply the behaviour factors, which are used to reduce the seismic loads accounting for ductile behaviour in the analysis. Their use implies that permanent displacements after an earthquake are allowed.

Special Solutions in Areas with High Seismicity

In areas with high seismicity it is favourable to have not only an elastic support of the turbine foundation combined with high damping but also a coupling of the substructure of a spring-supported turbine deck with the surrounding building. Usually the base mat of the turbine foundation is separated from the building by joints, but in an economic design and in case of a spring-supported deck it is possible to delete these joints and to integrate the columns into the surrounding load-bearing structure of the turbine house (*Fig. 7*). Without joints between machine foundation and building, major technical and economic advantages are possible, especially when considering seismic loads. It is, however, required to analyse the foundation and the building with one common model.

Some advantages of this integrated structure are:

- Less relative motion between turbine and surrounding structure, where even the absolute displacements are smaller compared to those of a conventional turbine foundation.
- Because of the high flexibility in the elastic support, turbine accelerations are reduced.
- Protection of the building, where the turbine foundation can work as a tuned mass damper. Because of the big mass, frequency shift and damping provide a positive influence in the whole structure of the building. This can be used for an economic optimisation, for example, as a reduction of cross-sections in the columns of the building.
- Simpler erection procedure, as no second row of columns around the turbine foundation is necessary.

Conclusion

The structural analysis of turbine foundations needs attention to detail both in modelling and interpretation of the results. In an appropriate model, beam elements or solid elements need to be decided on the basis of the foundation type. Particularly, the interpretation of the results of the dynamic analysis requires an understanding of the input data, delivered by the machine supplier. Dynamically isolated foundations can be a cost-effective and economic alternative, whereby the joint between machine foundation and surrounding structure can be omitted.

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