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Risks and Propsed Solutions for Dynamic Analysis of Offshore Structures

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Abstract—This paper focuses on two main matters. The first deals with the risks have been found in the dynamic analysis of offshore structures while the second is related to the proposed solutions of these risks. The main reasons of these risks are usually resulted from the simplifications of the domain of the whole problem (fluid-structure-soil) into subdomains (fluid-structures and structure-soil) so that these risks can be classified into three categories which are the loads estimation methods, the structural behavior assumptions, and the type of soil molding. The proposed solutions involve conservative method in load estimation, the investigation of imperfection of constructed structure, and the selecting accurate method for molding the soil condition including the seabed state and gap formation effect.

Index Terms— American Petroleum Institute API, Deterministic method, Offshore jacket, Reese solution, Pile response, Soil gap formation, Spectral method, Wave load, Winkler method.

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1 Introduction

The Offshore structures are structures that are built away from shore line and they primary related to the offshore exploration of oil and gas industry. They are responsibly considered as a modern marine structures compared with the onshore structures in which the first offshore industry structures is commonly considered as in 1947 in the Gulf of Mexico. Also, offshore structures may be defined by their two interdependent parameters, namely their function and configuration [1]. To date, there are more than 20,000 offshore platforms of various kinds installed around the world [2].

There is a rapid increase in the growth of offshore structures during last few decades due to many factors particularly in the different industrial developments like progressive in patrol and gas industry (oil exploration, production, processing, storage, and transportation). Recent advancements in construction materials, innovative structural forms, and methods of modeling and analysis make the understanding of the subject more broad-based.

These structures are different with the ordinary structures by many aspects such as the functions of the structures, the nature of applied load to resisted it, the analysis and design methods, the procedures of construction, the maintenance problems, and cost estimation of variety correlated operations of these structures, etc… so that the story of different risks associated with offshore structures are continuously increasing and stay with the time.

These different risks of offshore structures can be classified into the following categories [3],[4],[5],[6]:

1-Risks of constructions.
2-Risks of the analysis.
3-Risks of design.
4-Risks of economy.

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The jacket, the term jacket structure has evolved from the concept of providing an enclosure (jacket) for the well conductors, or template structures are still the most common offshore structures used for drilling and production. Fixed platforms are known as template structures, and they consist of the following [2]:

A jacket or tower is a welded space frame designed to facilitate pile driving.

Piles permanently anchored to the seabed to resist the lateral and vertical loads.

A superstructure consisting of the deck to support operational.

A sample of offshore structure designs are shown in figure 1.1 [7].

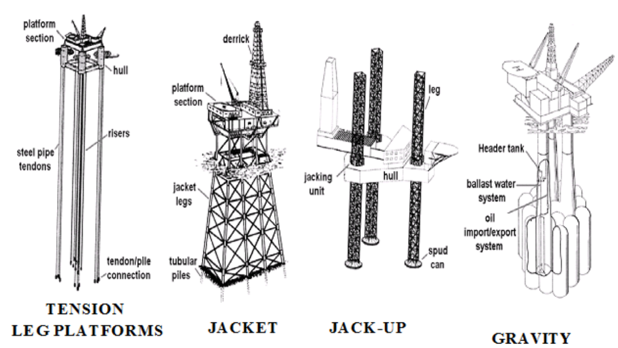

Figure 1.1: Sample of offshore structure dsigns

2 RISKS OF CONSTRUCTIONS

Three primary risks have been generated in the construction stage starting from the erection process to transporting and ending at the installation. In erection process, the different structures members are assembled and welded together to form the subassembly or main structure parts, then these parts are moved and to construct the structure. To overcome the risks in this process, first, it is recommended that and welding is at the ground level or undercover, second care should be exercised to ensure that no members or joints within the subassemblies are overstressed or distorted and the tolerances should be checked at each stage in accordance with the fabrication procedures, and in the final a structural analysis should be performed to check the structure members' stresses during the erection process.

In transporting process, all the activity shall be done on specified procedure from the lifting of the tower in fabrication yard and positioning to barge until setting in the sea. The check of lifting, loadout, and lunching forces that generated in this process must be investigated and the probable accident must be avoided and if occurred then re analyzed shall be made to decide the correct solution [8].

The beginning of the installation process start from lifting pile from the barge deck and ended at the complete pile hammering and welding topside part with the tower part.

The main risks of this process is buckling failure during installation and correct putting the piles and tower in place conditions which may be resulted from unreliable hammer type's selections, and bad weathering [9].

3 RISKS OF ANALYSIS

There are many methods of modeling and analysis of offshore structures which are highly complex, consequently, some degree of uncertainties are always associated with modeling and analyses methods.

These complications are caused by the complex domain of offshore structures which consist of many engineering systems such as the fluid part (including air and water), structure part, foundation- soil modeling that produce many risks and problems in the analysis stage such as the nature and definition of applied loads, the structural behavior of different offshore components, the support condition, and method of analysis.

The uncertainty of estimating applied loads represent main problem in the design of offshore structures. The applied loads on offshore structures involve the dead weight of offshore and its activity, the environmental loads of dynamic nature (wind, wave, ice, flow slide, current, seaquake, and earthquake), live loads (operation equipment and machines, and ship berthing and mooring). Additional loads are included such as the construction loads (the fabrication and installation loads which contain lifting, load out, transportation, launching, upending, and the accidental forces). All above loads are classified into static and dynamic types which may be taken the transient or repeat nature either one or two patterns.

3.1 Wave Loads

Wave load is considered the primary a part of the environmental loads in which is approximately representing 90 percent of these loads [2]. The waves are generally random in nature although in the ultimate load design method uses the deterministic methods [2,8,10]. The main problem related to the wave load is the method used to simulate the wave behavior because many wave theories had been developed from the past two centuries that are applied for deep, intermediate, and shallows water depth. Also, another problem of the wave load is the defined values of the main wave characteristics (wave height, wave length, wave duration, water depth, and wave direction) which are considered in the analysis. No unique solution is found for this problem although some recommendations are available as given by American Petroleum Institute API APIRP2A [10]. For example, the Stokes' theories are recommended for the deep and partially intermediate water and Conidal and solitary wave for shallow state. The following procedure is suggested by many references [7],[8],[9],[10],[11], and it used as criteria for the validation of wave theory used in the analysis: The limits for Ursell number U_R is used to as follows:

The cnoidal theory is applicable for $U_R > 25$,
Theory of Stokes is applicable for $U_R < 10$, and
Both theories are applied equally well for $10 < U_R < 25$,
In which Ursell number U_R is estimated as:

$$U_R = HL^2 / d^3 \tag{1}$$

where H= wave height, L= wave length, and d= water depth.

The maximum wave height depends on the location of offshore structure and reference [8] gives the maximum wind speed and maximum wave height for different locations in the world. Other wave parameters shall be investigated in the analysis by taking all the possible probabilities values so that the worse results will control the analysis.

But the problem is not completely solved because there are three different types of forces are exerted by water waves which are known as the normal force, the lift or lateral force, and the axial force and these forces values depend on the drag, inertia, lifting, and roughness coefficients which have a reasonable variations in their magnitude by many references and researchers so that many values may be resulted noting that the axial force is of minor importance and in many references this is not taken into account in the analysis while the first two kinds shall be extended to three dimensional analyses.

3.2 Soil Modeling

Pile foundations are frequently used for supporting offshore and onshore structures. Two possible risks may be produced when dealing with pile foundations. The first associated with the modeling method of soil response since through the past, many methods had been established to find an accurate solution using either the analytical, numerical, and experimental methods or procedures noting that the behavior of laterally loaded pile is a non-linear that different from the axially loaded pile which is frequently approximated to act as the bilinear (elastic-plastic) behavior. The second problem related to the establishing of the remote soil boundaries where the soil deformations in the static analysis (in other hand both deformation and velocity in dynamic analysis) are approximately become very small and reach zero value. Many recommended values are given but the difference between them is large as depicted in the references [12],[13] making selecting the accurate value so tedious and dangerous.

2.3 Soil Gap Formation

This problem must be distinguished from the secure formation due to the sea waves and currents. The gap formation is a phenomena which occurred around the pile head at the seabed location and this gap is created during the pile move-

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ments as a result of applied cyclic loads which leads to developed two state of stresses, the first is compressive stress in front of pile and second is tension in stress behind pile and when the soil cannot resist this tension stress which leads to a gap formation occurs around the pile as the soil was displaced by its entry as depicted in figure 2.1 [5],[12]. This gap is extended to a depth, measured from ground level, ranging from 3 to 8 pile diameters according to the various references [5],[14],[15].

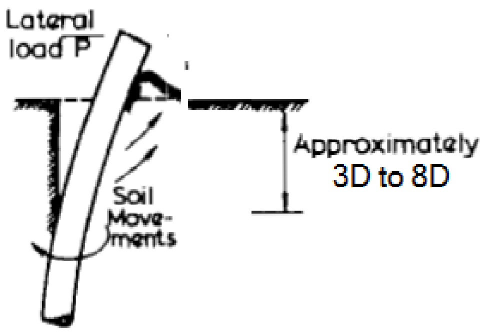

Figure 2.1: Sketch of gap formation under lateral load

3.4 Analysis Method

Each method of analysis for offshore structures is based on a number of assumptions which generally account for the inherent uncertainties [2]. For these structures, two nonlinearities effect have been aroused when dealing with both the fluid structure interaction and the soil structure (pile) interaction. All the related studies and researches make the separation of the problem domain into two primary types well-known namely the fluid-structure interaction and the soil-structures interaction [16]. For this purpose, the following procedure is adopted by different researchers [16],[17],[18]:

The analysis is carried out into two stages. In the first, the analysis is done for fluid passing structure considering the structure is fixed at their support nodes, a small distance below seabed level to allow for scour effect, and the reaction forces are determined, after that these reactions are used in the soil structure interaction. The free and forced vibration analysis scheme for both interaction types are used in the similar manner.

But another problem is developed about the efficient method of modeling both interaction types. The answer of this problem is gone into two different analysis procedures which well known as the deterministic approach in which all necessary parameters of the analysis can be uniquely determined while the second is the stochastic approach for which the statistical characteristics are calculated to be used further in the determination of structural behaviors in probabilistic pattern [2],[8]. Many references [2],[10],[16],[17],[19] use the deterministic procedure for ultimate load design method as existing of the extreme wave loading and berth loading while the stochastic approach is used to investigated and checked the fatigue and cracks the at joints of offshore structures for loads such as the earthquakes and sea waves which occur in arbitrary fashions.

4 RISKS OF DESIGN

In dealing with the design of marine structures many uncertainties are unavoidable. Uncertainties are broadly classified into two types: (i) those associated with normal randomness and (ii) those associated with erroneous predictions and estimations of reality different degrees of simplifications are made in the reliability estimates of marine structures [20]. Two basic risks may be happened in the design stage, the first associate with the material properties estimation such as the modulus of elasticity of concrete, steel, and soil under different loading conditions while the second with the fracture phenomena in the steel members and joints due to the fatigue or shape effect of steel member.

But the fatigue damage represent the main problems in the offshore structures which occurs in two main stages as being crack initiation and crack growth including propagation of one dominant crack and the final fracture [19],[20],[21],[22]. For example, "API [10] says: A detailed fatigue analysis should be performed for all structures and the recommendation is given for a spectral analysis technique to be used". One of important source of cracks in offshore structures is the metal micro cracks which are formed at the weld toe during welded fabrication stage as a result of weld cooling. To carry out the assessment of cumulative fatigue damage, a several factors must be well established which include the environmental conditions, hydrodynamic loading, structural modeling. soil-structure interaction modeling, procedure for determining the stress response, stress concentration factors, the stress cycles experienced and their stress range, and fatigue damage rule [21],[22] noting that the long-term variations of local stress are generally caused by environmental loads, predominantly by waves and wind directions loads.

There are three important methods of fatigue assessment which are (i) the simplified method, (ii) the spectral method, and (iii) the deterministic method. Common design approach is to use S–N curves with stochastic methods while deterministic method is less common in practice [19]. In addition, is to be noted that the specified S–N curve used in the hot spot approach will not account for local geometric changes. Therefore, it is necessary to perform a detailed structural analysis to determine explicitly the stress concentrations due to such changes.

5 RISKS OF ECONOMY

Each stage of offshore structure life is an expensive due to the demand and needing of the special material, jobs, employers, equipment, and tools. Therefore, any saving in any part of these stages represents an economic goal and target. The main objective of any project is to satisfy their function with adequate degree of safety otherwise one error is occurs that is the loss in their function or the loss in money. For example, the driven pile into the soil represent the most expensive stage compared with other stages knowing that the

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embedded pile depth into the soil must be satisfactory to transform the loading to the soil but if this depth is larger as required a significant loss in money well be happened so that who well choose this depth and what is the criteria to modify this decision. This problem is well stated in the case study in the following paragraphs.

6 CASE STUDY

In order to investigate the effect of the most possible risks which are mentioned in the past paragraphs a real offshore structure shall be selected so that the dolphin of khor Al-Amaya berth no. 8 which shown in figure 6.1 is taken as case study for the following reasons. The first because this structure is a real structure with optimal dimensions and components, and the second associated with many researchers who used this structure with different formulations [17],[23]. Finally, this structure has two pile types that are vertical and battered piles because the foundation consist of 8 piles with a different piles orientations vertical and batter one and two directions.

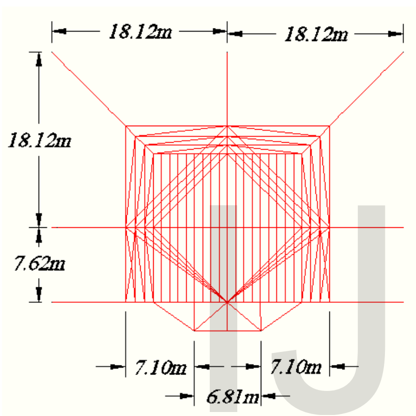

Figure 6.1.a: Top view

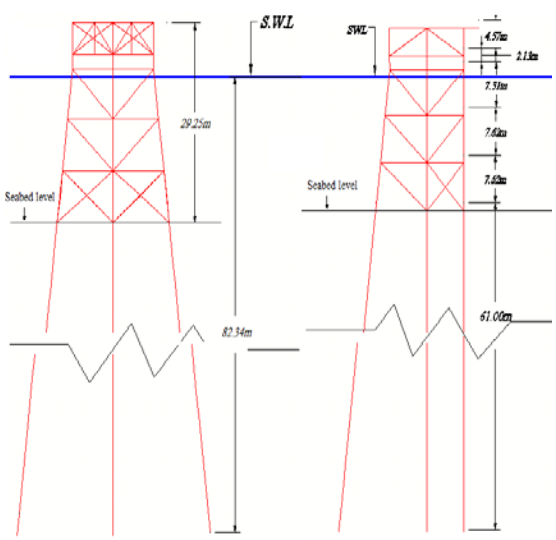

Figure 6.1.b: Front and side view

Figure 6.1: Structural details of the dolphin of khor Al-Amaya berth no. 8

6.1 Wave Loads

6.1.1 Wave Theory Type

Table 1 shows the variation of maximum deck deflection and maximum base axial force (noting that the maximum shear force and maximum bending moment have similar trend to axial force therefore their results are not given here) with wave length using Airy, Stoke, and Cnoidal wave theory noting that Ursell number is used as a criteria or a constraint in applying different wave theories. From tables 6.1, it is found that the increase in wave length causes increase in the structural response until wave length is equal to 900 m (Ursell number=892), after that no increase is appeared for Cnoidal theory. The reason for these results can be explained as follows:

For large Ursell number the wave profile is reaching to the profile of solitary wave as wave parameter m approaching one. Also, this table display clearly that the Airy theory is not suitable to be used in the analysis for shallow water and their results have a great difference with respect to Cnoidal theory.

Table 6.1: The variation of maximum deck deflection (mm) with wave length using various methods of analysis and wave theories

Wave length (m)	Wave theory type	Method of analysis			
		SMN	SMT	SSN	SST
100	Airy	13.0	12.8	13.0	12.8
	Stock	21.0	20.7	21.1	20.9
	Cnoidal	19.7	19.4	19.8	19.5
200	Airy	14.3	14.4	14.3	14.4
	Cnoidal	29.0	28.9	29.0	28.9
300	Airy	14.3	14.3	14.4	14.4
	Cnoidal	50.5	50.5	50.5	50.5
400	Airy	14.2	14.2	14.3	14.3
	Cnoidal	63.2	63.1	63.2	63.2
500	Airy	14.2	14.1	14.2	14.2
	Cnoidal	67.4	67.4	67.4	67.5
600	Airy	14.2	14.3	14.3	14.4
	Cnoidal	72.2	72.2	72.2	72.3
700	Airy	14.5	14.6	14.6	14.6
	Cnoidal	74.2	74.3	74.3	74.4
800	Airy	14.6	14.6	14.6	14.7
	Cnoidal	76.4	76.6	76.5	76.6
900	Airy	14.6	14.6	14.7	14.7
	Cnoidal	83.1	83.2	83.3	83.2
1000	Airy	14.9	14.9	15.0	15.0
	Cnoidal	83.1	83.2	83.3	83.2

SMN: Static method using Morison equation including in normal hydrodynamic forces only.

SMT: Static method using Morison equation including both in normal and lift hydrodynamic forces.

SSN: Static method using Sarpkaya equation including only in normal hydrodynamic forces.

SST: Static method using Sarpkaya equation including both in normal and lift hydrodynamic forces.

6.1.2 Wave Direction Effect

Figure 6.2 displays the effects of wave direction on the maximum deck displacement where these results represent the maximum effects based on SST method for wave length equals 900 m and using Cnoidal theory. In this figure, the wave direction value is taken from zero to 360º to cover all possible probability that may be caused the worse effect. It is seen from figure 6.2 that the direction of wave has considerable effects that are mainly depending on the geometry layout of the analyzed structure and type of method of analysis. For the structure analyzed here, the results show the main effects of wave direction occurred in the direction of ship berthing that represent the critical case in the analysis.

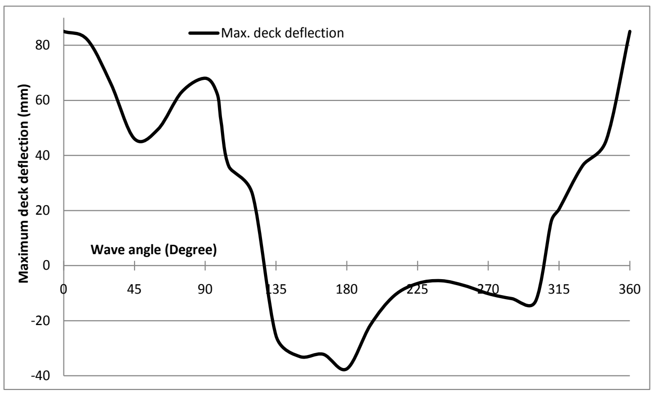

Figure 6.2: The variation of maximum deck deflection with wave direction based on SST method for wave length 900 m by Cnoidal theory.

6.2 Soil Modeling

The same structure had been analyzed for the impact ship load using three berthing velocities by two soil finite element method modeling. In first case, the modeling of soil was done by introducing a nonlinear springs (Winkler method) along pile length [17] while in the second method the three dimensional interface element was development to simulate the pile-soil interaction [6]. In both method the (p-y), (t-z), and (q-z) curves are used to derivative the nonlinear soil reaction moduli [10].

Table 6.2 shows the main item from two methods such that:

1-Increasing soil strength causes decreasing the maximum structural response for clay soils and sand soils because of increasing the domain stiffness.

2-It is noted that the loading time of velocity one has a small effect on maximum deck displacement in which DAF value is equal to 13% associated to stiff clay. This effect may be explained due to large contact time that reduced dynamic response as indicated by the previous method. For zero contact time that represents the worst case which may be happened in real world, the response increased by different amount according to deck displacement and base reactions.

3-Interface formulation is more response than Winkler method by a responsible amount. As example for stiff clay, the maximum structure deflection increase by 49% for zero contact time and 79 % for static (50 sec). The other items have the similar trend.

Also, table 6.3 shows the maximum deflection and critical length, length from seabed corresponding to first zero pile deflection, for clayey soils using elastic [24], interface [6], and Reese solution [25]. This result can be explained from the stiffness of elastic model is greater than the other models.

Table 6.2: The effect of loading time on structural response for different soil types using different problem formulation

Item (maximum value)	Zero contact time			2.4 contact time			Static (50 sec)		
	Interface		Winkler	Interface		Winkler	Interface		Winkler
	Stiff clay	Dense sand	Clay	Stiff clay	Dense sand	Clay	Stiff clay	Dense sand	Clay
Structure deflection (mm)	79.0	81.3	53.1	54.3	56.6	29.7	51.3	54.9	29.0
Base axial force (kN)	2071	2112	1568	1485	1513	887	1432	1468	867
Base shear force (kN)	457	455	536	262	253	299	269	244	293
Base bending moment(kN.m)	2079	2244	805	1137	1219	450	1082	1174	440
Dynamic amplification factor	1.54	1.48	1.83	1.06	1.03	1.02	1	1	1

Table 6.3: The Pile Maximum Deflection and Critical length for Different Clayey Soils Using Elastic, Interface, and Reese solution

Method of Solution	Maximum deflection (mm)			Critical Length (m)		
	Soft Clay	Firm Clay	Stiff Clay	Soft Clay	Firm Clay	Stiff Clay
Elastic Solution	-12.39	-7.13	-3.76	5.66	5.66	6.01
Program Fortran	-30.09	-19.90	-10.60	15.71	13.80	11.15
Matlock and Reese	-16.37	-9.42	-4.97	14.15	11.89	10.00
Fortran/Elastic Ratio	2.43	2.79	2.82	2.78	2.44	1.86
Fortran/Reese Ratio	1.84	2.11	2.13	1.11	1.16	1.11

6.3 Soil Gap Formation

Gap or partially losing pile – soil contact effect is clearly noticing in table 6.4. Since the applied load is transmitted to soil via the pie foundation even the gap formation is existed or not but the effect is the how the pile forces variation. Also in table 6.4, it is obvious the gap occurred increases the bending moment approximately twice than without gap aroused and a similar behavior is seen for the axial force with less ration but the shear force has a different story. The reason for this result is so simple because the gap effect makes the foundation more flexible leading to increase the pie response and for the shear forces this gap make another effect which is the redistribution of forces between the piles foundation. Therefore, it is strongly recommended to make protection work at sea bed to eliminating this problem.

Table 6.4: The effect of gap formation around the pile head on the maximum pile responses

Item	Including Gap Effect			Excluding Gap Effect		
	Soft Clay	Firm Clay	Stiff Clay	Soft Clay	Firm Clay	Stiff Clay
Axial Pile Deflection (mm)	10.3	6.3	5.6	7.7	5.2	4.2
Normal Pile Deflection (mm)	42.4	40.1	25.5	22.6	13.0	6.2
Axial Force (kN)	2018	1847	2019	1741	1634	1914
Shear Force (kN)	387	404	410	375	415	479
Bending Moment (kN)	2340	2125	1669	1205	1053	709

6.4 Risk of Economy

Broadly speaking, the pile foundation represents the major construction problem for fixed offshore structures and as mentioned in the related paragraph any reduction of the pile length based on an engineering approach mean an economic golden goal for any company or contractor. The structures of case study here was built in last century before many techniques had been found such as the finite element method, the interface method and a similar methods and as seen in table 4 the critical pile length which play an important factor in the design of pile for lateral load equal for worst cases to half of constructed pile length (60.0 m) which mean high over design value. By using the available techniques today, the design of offshore pile foundation is become so economic without an unexpected risk.

7 CONCLUSIONS

From previous results, the following conclusions can be with drawn:
1- By using Cnoidal theory, the wave length plays an important factor on increasing the structure response by a large amount until Ursell number approximately approaching to 1000, after that the wave behavior is converted to the solitary type and no changes in the structure response are noted or occurred.
2- The time of load raising has an important effects on the structural response for both the Winkler and interface method but the results of first method are more sensitive (increased by 83%) than the second method (increased by 54%).
3-The Winkler method based on (p-y), and (t-z) curves displays a lower structural response by a reasonable amount compared (more than 80%) with the interface method using the same curves.
4- The wave direction is an important property which has a great influence on structural behavior.
5- Gap formation causes to increase the pile bending moment twice than ignoring it.

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