17th International Conference on
Offshore Mechanics and Arctic Engineering

OMAE98-1460

MODIFICATIONS TO DNV MOORING CODE (POSMOOR) AND THEIR CONSEQUENCES

Bjørn Egeberg Sogstad
Det Norske Veritas
Høvik
Norway

Jan Mathisen
Det Norske Veritas
Høvik
Norway

Torfinn Hørte
Det Norske Veritas
Høvik
Norway

Halvor Lie
Marintek
Trondheim
Norway

ABSTRACT

DNV's mooring code, given in the Rules for Classification of Mobile Offshore Units and known as POSMOOR, will be modified in accordance with the findings of the joint industry project "Reliability-Based, Cost-Effective, Design Methods for Deep Water Mooring Systems - DEEPMOOR". Other international mooring codes and DNV's code are currently based on formats with a single safety factor or utilization factor. This format will be replaced by a limit state format, which is already widely used in the oil offshore industry.

The code will be reformulated in terms of three limit state functions: ULS (Ultimate Limit State), PLS (Progressive collapse Limit State) and FLS (fatigue limit state).

The partial safety factors involved in the limit state functions will be based on calibration against structural reliability analyses. An alternative formulation of the characteristic strength of mooring line components will be introduced, based on component test data. If such data is not available, then the characteristic strength can still be derived from the conventional minimum breaking strength.

INTRODUCTION

National Authorities and Classification Societies have design rules, which contain requirements with respect to the utilization of the strength of mooring lines for drilling, floating production, and storage units. The utilization is expressed as a safety factor. The permissible safety factor is defined as:

$$SF = \frac{P_b}{T_{max}} \tag{1}$$

Where P_b is the minimum breaking strength of the anchor line (adjusted for corrosion allowance) and T_{max} is the maximum tension in the most heavily loaded line.

The Norwegian Maritime Directorate (NMD) introduced rules regarding positioning systems in 1973. This original rule did not contain specific safety factors. The safety factors were introduced in 1982. The American Petroleum Institute introduced API RP 2P in 1987 (second edition). DNV's mooring code was first issued in January 1984.

RULES AND REGULATION TODAY

For the final design of a long term (permanent) mooring, intended to operate in open seas; i.e. not in the vicinity of another installation of any kind, the American Petroleum Institute (API), American Bureau of Shipping (ABS), Lloyd's Register (Lloyds), Det Norske Veritas (DNV), and the Norwegian Maritime Directorate (NMD) give the safety factors for anchor lines shown in Table 1, with respect to extreme environmental conditions.

TABLE 1. COMPARISON OF SAFETY FACTORS FOR ANCHOR LINES

Source (see Refs.)	Condition			
	Intact	Single failure	Double failure	Transient Motion
API	1.67	1.25	-	1.05
ABS	1.67	1.33	-	-
Lloyd's	1.85	1.35	-	1.10
DNV	1.50	1.10	-	1.00
NMD	1.65	1.25	-	1.00
NMD[1)]	2.30	1.50	1.50	1.2

[1)] Double failure is a design requirement for floating production and storage units required by Norwegian Petroleum Directorate (NPD) and NMD for extreme environmental condition when production is terminated and the risers are still connected.

The use of the above safety factors requires that dynamic analyses are used for determination of anchor line forces. It is also important to note that the definition of extreme condition differs between the mooring codes given in Table 1. For instance, API requires a return period of 100 years for permanent moorings and 5 years for mobile moorings. DNV and NMD require 100-year return periods for all types of units.

NEW MOORING CODE

This section introduces the proposed changes to the DNV mooring code (POSMOOR). All the changes are based on results of the Joint Industry Project: "Design Methods for Deep Water Mooring Systems – DEEPMOOR" (Hørte et al., 1998, Mathisen et al., 1998). The sub-sections below have titles with direct reference to the relevant sections in the present rules. Instead of the format in equation (1), the limit states are typically formulated as:

$$\textit{Design capacity} - \textit{Design load} \geq 0$$

where the design value is usually the product or quotient of a partial safety factor and a characteristic value. The characteristic

values are obtained according to well-defined recipes, and the partial safety factors have been calibrated by a more refined structural reliability analysis, to ensure that the simplified design rule leads to the target reliability.

Characteristic Tensions

Environmental Conditions (Section 2 A102)

The environmental actions to be applied in the mooring line response computations are to be based on wind and wave conditions with 100 year return periods, together with current with a 10-year return period. Collinear actions are adequate for mooring systems with fixed headings, but non-collinear actions must also be considered for turret-moored systems. A wind heading at 30 degrees, and a current heading at 45 degrees, both relative to the wave heading, should be considered in that case.

The wave conditions are to include a set of combinations of significant wave height and peak period along the 100-year contour. The 100 year contour is to be determined using the inverse FORM technique (ref. Winterstein et al. 1994).

Low frequency motion (Section 2 B300)

Extreme low frequency (LF) motion is to be calculated using the Rayleigh distribution:

$$X_{LF}^{\max} = \sigma_{LF} \cdot \sqrt{2 \ln N} \qquad (2)$$

Where:

$X_{LF}^{\max}$ = The probable largest LF motion response

σ_{LF} = Standard deviation of LF motion response

$N = t/T_{LF}$ = The number of motion cycles, with t as the storm duration in seconds, and is to be at least 3 hours.

$T_{LF} = 2\pi\sqrt{\frac{m}{k}}$ = The natural period of the vessel's LF motion.

m unit mass including added mass in kg

k mooring system stiffness in N/m taken at the vessel's mean position.

Quasi-static Analysis (Section 3 A200)

The existing rule accepts that LF motions may be omitted for column-stabilized units that are insensitive to LF motion. This is less relevant today, because the displacement of column stabilized-units is now much larger than for units built 20 years ago. In the new rule revision LF motions are to be considered without exception.

Calculation of Offset and Line Tension (Section 3 A200)

The maximum excursion is to be calculated by combination of LF and Wave frequency (WF) motions as follows:

$$X_{TOT} = X_{mean} + X_{LF}^{\max} + X_{WF}^{sign} \quad \text{when } X_{LF}^{\max} > X_{WF}^{\max} \qquad (3)$$

$$X_{TOT} = X_{mean} + X_{WF}^{\max} + X_{LF}^{sign} \quad \text{when } X_{LF}^{\max} < X_{WF}^{\max} \qquad (4)$$

Where:

X_{TOT} = Quasi-static position of the unit at which the line tensions are calculated

X_{mean} = Mean offset (equilibrium position) due to static loads caused by wind, wave and current

$X_{WF}^{\max}$ = Maximum wave frequency offset

$X_{LF}^{\max}$ = Maximum low frequency offset

X_{WF}^{sign} = Significant wave frequency offset

X_{LF}^{sign} = Significant low frequency offset

The quasi-static line tension is calculated at the above excursion from the initial position.

Calculation of Dynamic Line Tension (Section 3 A300)

The dynamic analysis should include the LF motion caused by wind and waves. The current may be taken as constant. Frequency domain analyses are to be applied, where the non-linear damping and restoring forces are approximated by a stochastic linearization method as follows:

- Calculate the natural frequency of the mooring system
- Calculate spectral density of LF excitation due to wind and waves at the natural frequency.
- Estimate damping ratio for the unit including contribution from the mooring system.
- Calculate standard deviation of the low frequency response using a constant excitation spectrum given by the spectral density at the natural frequency.

The Society accepts an analysis method whereby the LF behavior of the moored unit is analyzed separately from the WF behavior of anchor lines by superimposing the global response analysis to arrive at the total line tension.

The total line tension is the maximum of the following combinations of quasi-static and dynamic tension

1. Quasi-static tension at position:

   $$X_{\max} = X_{mean} + X_{LF}^{\max} \qquad (5)$$

   Combined with the significant value of the wave frequency tension calculated at this position
2. Quasi-static tension at Position:

   $$X_{\max} = X_{mean} + X_{LF}^{sign} \qquad (6)$$

   Combined with the most probable largest value of wave frequency tension calculated at this position

The maximum wave frequency tension is calculated using a Rayleigh distribution.

Calculation of Transient Motion (section 3 A400)

In the DEPMOOR project it has been documented that the transient motion is not a governing case compared to the design check after one line has failed, in the presence of realistic levels of oscillatory environmental loads (Mathisen et al., 1998). Transient response could be important if there are heavy static loads and no oscillatory loads, but this is normally unrealistic. Requirements to

transient motion calculation are therefore omitted from the new rule revision.

Method Factor

Calibration of a design rule by structural reliability methods tends to generate an insistence on strict adherence to a well-defined recipe for the characteristic load and capacity, to ensure that the target reliability is attained in application of the design rule. This practice can be unfortunate, because it discourages the designer from using improved analysis methods that deviate from these recipes, such as time domain analysis and model tests. This effect has been highlighted in the present case where the chosen recipe for low-frequency tension is known to be unconservative in some cases. (This shortcoming in the recipe is taken into account in the calibration of the partial safety factors.) In such cases, a more detailed analysis would lead to higher loads and tend to penalize a conscientious designer. We have introduced the concept of a method factor to improve the situation.

If a more refined analysis method is used to compute the mooring line tension, then the refined tension may be multiplied by a method factor, to yield an alternative characteristic tension, for use in the design equation. Two alternative ways of obtaining the method factor can be envisaged: (a) a case dependent method factor - computed by comparing the two tension results for a particular mooring system, and (b) a more general method factor - obtained by comparing the calibration results for two alternative methods. We are pursuing alternative (b), for a method factor which is not dependent on one particular mooring system case. A calibration of an alternative method has been carried out. This method uses a more accurate distribution function for the low-frequency motion and special consideration of the effect of quadratic drag force on the maximum of the wave-frequency tension. Based on these results, a method factor of 0.95 has been selected for the ULS and 0.90 for the PLS, with reference to the dynamic tension component in both cases. It is suggested that the same method factors can also be applied to other refined analysis results than the one we have calibrated, provided the designer shows that the applied method is more accurate than the basic recipe for the characteristic dynamic tension and that the applicability of the input data to the analysis is well-documented.

The method factor is only expected to be useful for the dynamic tension component. The method factor does not explicitly give any credit for reduced model uncertainty due to more accurate analysis methods. Structural reliability analysis is required to achieve this, and is acceptable as an alternative to use of the simplified design analysis.

Operating Conditions (Section 3 B100, B200)

The POSMOOR Rules have defined two different Operation Conditions depending on type of operations for the unit. Different safety factors are defined for each operation condition. This concept will be omitted, and a new concept with consequence classes is introduced. This concept is applicable to all types of moored units. In addition new safety factors are introduced based on the calibration carried out in the DEEPMOOR Project.

Limit state definitions:

- ULS: Ultimate limit state, which is defined as failure due to tensile overload of any component in one line of the mooring system. Annual probability of failure is 10^{-4}.
- PLS1: Progressive collapse limit state 1, which is defined as failure due to overload of any component in any line of the mooring system, after one line has initially failed due to exceptional causes. Annual probability of failure is 10^{-5}.
- PLS2: Progressive collapse limit state 2, which is defined as failure due to overload of any component in any line of the mooring system after one line has initially failed due to exceptional causes. Annual probability of failure is 10^{-6}.
- FLS: Fatigue limit state. Failure due to fatigue of any component in one mooring line of the mooring system. Safety factors on the design life, based on reliability analyses, are not yet finalized.

PLS1: To be applied when loss of position does not lead to a critical situation for the overall safety of the unit and those on board; e.g. for drilling units with the riser disconnected and for floating production or storage units far away from other installations, with riser(s) disconnected or production terminated, and pressure sources isolated.
PLS2: To be applied when loss of position leads to a critical situation for the overall safety of the unit and those on board; e.g. for accommodation units close to other installations, drilling units during drilling operation, and floating production or storage units with the risers connected producing hydrocarbons.

Minimum Breaking Strength (Section 3 C100)

The minimum breaking strength is currently applied as the characteristic strength in mooring line codes. The reliability analyses demonstrate that consistent component quality, as quantified by the mean value and coefficient of variation of the breaking strength greatly affects the line reliability.

The design capacity is set equal to the characteristic strength:

$$S_C = \mu_s[1-\delta_s(3-6\cdot\delta_s)] \quad \delta_s < 0.25 \qquad (7)$$

Where μ_s is the mean strength and δ_s is the coefficient of variation of the actual component breaking strength.

Characteristic line strengths equal to the minimum breaking strength may for example be obtained if:

- the mean strength of an individual chain component is 1.1 times the minimum breaking strength and the coefficient of variation is equal to 0.03, or
- the mean strength of an individual chain component is 1.4 times the minimum breaking strength and the coefficient of variation is equal to 0.13

The equation above is to be applied provided relevant test data are available for the component considered. If such data are unavailable, the characteristic strength is to be set equal to the minimum breaking strength multiplied by a reduction factor of 0.95. Old components may need a lower factor.

Design Equation Format for ULS and PLS (Section 3 C100)

Partial safety factors for the design equations have been evaluated by calibration of the design equations against reliability analysis results in the DEEPMOOR Project. A target annual probability of failure of 10^{-4} has been applied in the calibration for the ultimate limit state (ULS). Two formats for the design equation have been considered:

a) Quasi-static mooring system analysis with a single safety factor,

b) Dynamic mooring line analysis with two safety factors.

Design format b) is required for water depths of 200 m or more. The two tension components in format b) are:

- the static tension due to pretension and tension induced at the offset position corresponding to the mean environmental forces in an environmental state, and
- the dynamic tension due to time varying loads; i.e. the sum of time varying LF and WF tensions in the environmental state.

The target annual probabilities of failure of 10^{-5} and 10^{-6} have been applied in the calibration of the progressive collapse limit state (PLS1 and PLS2)

The tentative safety factors are given in Table 2. The results for the ULS have been thoroughly discussed, while the results for the PLS are quite recent and liable to be modified before the revised POSMOOR rules are published.

TABLE 2 TENTATIVE SAFETY FACTORS FOR ULS AND PLS

Limit State	Quasi-static analysis	Dynamic analysis	
		Static	Dynamic
ULS	1.66	1.10	1.52
PLS1		1.00	1.23
PLS2		1.30	1.80

MOORING CALCULATIONS

Trial mooring calculations are carried out according to the present rule format, and in accordance with the proposed ULS and PLS format. The results are compared with respect to calculation of mooring line tension and offset. Two different mooring concepts have been investigated:

- Drilling unit with 8 mooring lines equally spread. The mooring system is designed in accordance with DNV POSMOOR Rules, Operation Condition I.
- Floating Production Unit, with 16 mooring lines arranged in 3 bundles of 4 lines each. The mooring system is designed to comply with DNV POSMOOR Rules Operation Condition II.

The mooring analysis program MIMOSA 5.4-01 (Lie, 1990) is used in the calculations.

- Operation Condition I is defined as follows:
  Position mooring where a single failure of positioning system will not lead to a critical situation for the overall safety of the unit and those on board. Typically a drilling unit in survival condition with the riser disconnected.
- Operation Condition II is defined as follows:
  Position mooring where exceedance of position limitations will lead to a critical situation for the overall safety of the unit and those on board. Typically for a unit designed for production and/or injection of oil, water or gas through a system consisting of one or several rigid or flexible risers, and associated well control umbilicals, when the unit is in production mode.

Semisubmersible

The mooring system consists of 8 lines with particulars according to Table 3. The water depth is 500 m. The mooring pattern is shown in Figure 1

Environmental criteria and corresponding environmental loads used in the calculation are given in Table 4. The Jonswap spectrum is used with a peakedness parameter of 5, which is in accordance with DNV Classification Note 30.5

Results according to present code format

The mooring system has been checked with respect to Operation Condition I (Survival) with the results shown in Table 5.

Mooring System Design according to the new recipe

The total line tension is found to be a maximum for the following combinations of quasi-static and dynamic tension

1. Quasi-static tension at position:

$$X_{\max} = X_{mean} + X_{LF}^{\max} \tag{8}$$

Combined with the significant value of the wave frequency tension calculated at this position

2. Quasi-static tension at Position:

$$X_{\max} = X_{mean} + X_{LF}^{sign} \tag{9}$$

Combined with the most probable largest value of wave frequency tension calculated at this position

The characteristic strength of the mooring line is 8167 kN multiplied by 0.95 which is 7759 kN. The mooring system satisfies the ULS and PLS1 criteria

TABLE 3 MOORING LINE DATA FOR DRILLING UNIT

Dimension	Stud Chain	Length	Distance Anchor-fairlead	Minimum breaking strength
90 mm	NV R4	1600 m	1398 m	8167 kN

TABLE 4 ENVIRONMENTAL CRITERIA AND LOADS FOR DRILLING UNIT

Environmental criteria		Environmental Loads
Wind (1 hour mean)	38.0 m/s	3255 kN
H_s =	14.7 m	152 kN
T_p =	14.5 sec.	
Surface Current	1.3 m/s	713 kN

TABLE 5 RESULTS FOR DRILLING UNIT ACCORDING TO PRESENT CODE FORMAT

Heading: Bow Quartering, (225° relative to North)				
Intact/Line broken	**Tension (kN)**	**Highest tension in line no.**	**Safety Factor**	**Required Safety Factor**
I	5076	2	1.61	1.5
1	6661	2	1.23	1.1

FIGURE 1 MOORING PATTERN FOR DRILLING UNIT

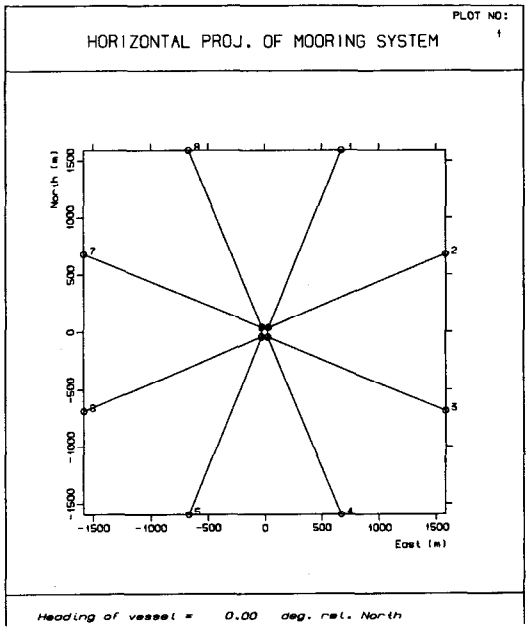

TABLE 6 RESULTS FOR DRILLING UNIT ACCORDING TO THE NEW RECIPE

Limit State	Method	T_{mean} (kN)	T_{LF}^{Max} Or T_{LF}^{Sign} (kN)	T_{WF}^{Sign} Or T_{WF}^{Max} (kN)	Design Tension (kN)
ULS	1	2905	529	731	5111
	2	2905	300	1255	5559
PLS1	1	3960	923	1031	6363
	2	3960	533	1696	6702
PLS2	1	3960	923	1031	8665
	2	3960	533	1696	9160

Floating Production unit (FPSO)

The mooring system consists of 16 lines with particulars according to Table 7. The water depth is 125 m. The mooring pattern is shown in Figure 2. The horizontal distance between anchor and fairlead is 1367 m. The chains have a corrosion allowance of 0.4 mm/year. The design life of the mooring system is 25 years. At the end of the design life the diameter of the chains have been reduced with 10 mm, corresponding to a chain with a diameter of 120 mm, and a breaking strength of 13573 kN.

Environmental criteria and corresponding environmental loads used in the calculation are given in Table 8. Wind, waves, and current are collinear. The Jonswap spectrum is used with a peakedness parameter of 1.1.

Results according to present code format

The mooring system has been checked with respect to Operation Condition II with results as shown in Table 9.

Mooring System Design according to the new recipe

The total line tension is found to be the maximum for the following combination of the following combinations of quasi-static and dynamic tension

1. Quasi-static tension at position:

$$X_{\max} = X_{mean} + X_{LF}^{\max} \tag{10}$$

Combined with the significant value of the wave frequency tension calculated at this position

2. Quasi-static tension at Position:

$$X_{\max} = X_{mean} + X_{LF}^{sign} \tag{11}$$

Combined with the most probable largest value of wave frequency tension calculated at this position

The results presented in Table 10 only include alternative 1, since this method of calculating line tension was governing in this case.

The characteristic strength of the mooring line is 13573 kN multiplied by 0.95 which is 12894 kN. The mooring system satisfies the ULS, PLS1 and PLS2 criteria.

TABLE 7 MOORING LINE DATA FOR FPSO

Line segment	Dimension (mm)	Type	Length (m)	Breaking strength (kN)
Top	130	Studless Chain	150	15559
Middle	122	Spiral strand wire rope	770	13500
Bottom	130	Studless Chain	480	15559

TABLE 8 ENVIRONMENTAL CRITERIA AND LOADS FOR FPSO

Environmental criteria		Environmental Loads
Wind (1 hour mean)	38.0 m/s	1309 kN
H_s = T_p =	14.0 m 14.0 sec.	1194 kN
Surface Current	1.3 m/s	147 kN

TABLE 9 RESULTS FOR FPSO ACCORDING TO PRESENT CODE FORMAT

Heading: Colinear towards the bow , (180° rel. to North) Line Tensions at Chain Stopper				
Intact/Line broken	**Tension (kN)**	**Highest tension in line no.**	**Safety Factor**	**Required Safety Factor**
I	5654	7	2.40	2.30
6	6724	7	2.02	1.50

FIGURE 2 FPSO MOORING PATTERN

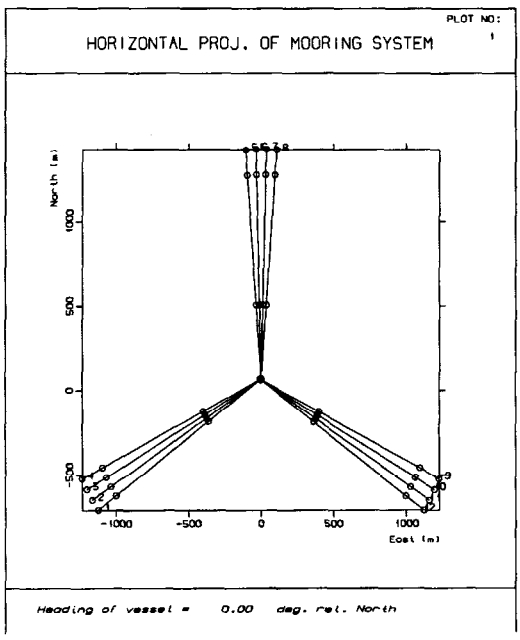

TABLE 10 RESULTS FOR FPSO ACCORDING THE NEW RECIPE

Limit State	T_{mean} (kN)	T_{LF}^{Max} Or T_{LF}^{Sign} (kN)	T_{WF}^{Sign} Or T_{WF}^{Max} (kN)	Design Tension (kN)
ULS	1645	2715	660	6940
PLS1	1996	3255	767	4947
PLS2	1996	3255	767	9834

CONCLUSION

The modified code presented above differs from the present code in the following ways:

1. A limit state format is applied rather than a single safety factor or utilization factor format.
2. A more uniform reliability level is obtained by separating the applied load into two characteristic tension components with associated partial safety factors, in both the ULS and PLS.
3. The recipe for the characteristic tension is simplified, by using a Rayleigh distribution.
4. The definition of the characteristic capacity allows for the use of component test data or the conventional minimum breaking strength.
5. The reliability level of the code has been quantified by calibration against structural reliability analysis.
6. Two consequence classes are incorporated in the code and the difference in reliability level for the two classes is quantified.
7. The scope of applicability of the code is based on the test set used in the calibration, which includes mooring systems for a turret-positioned ship and a semisubmersible, in water depths from 70 m to 2000 m, and environmental conditions for both the Norwegian continental shelf and the Gulf of Mexico.
8. The structural reliability analysis applied in the calibration is available as an alternative to the simplified design code, with a consistent reliability level, if more detailed analysis is desired.

The present code requires the non-Gaussian nature of the line tension process to be considered and leads to characteristic line tensions which are typically 6 – 12% larger than those calculated with the new recipe. This difference is partly offset by a 5% reduction in the characteristic strength, when this is based on the minimum breaking strength..

The calibration carried out in the reliability analysis has taken both concepts into account. The plan is to introduce the new format in the next revision of DNV Rules for Position Mooring (POSMOOR).

ACKNOWLEDGEMENTS

This paper presents some of the results from the DEEPMOOR joint industry project. The authors gratefully acknowledge the support of the participants in the project: Advanced Production and Loading, Bridon International, Conoco Norge, Det Norske Veritas, the Health and Safety Executive, Lloyd's Register, Norsk Hydro, Norske Shell, the Norwegian Maritime Directorate, the Norwegian Shipowners' Association, the Royal Norwegian Research Council, Scana Ramnäs, Statoil, and Vicinay Cadenas. The project has been carried out in cooperation between Det Norske Veritas and Marintek. The material presented herein should not necessarily be taken to represent the views of any of these companies.

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