Analysis of Torpedo Anchors for Mooring Operations

S. Keerthi Raaj, R. Sundaravadivelu, and Nilanjan Saha

Abstract A novel technique of dynamically installing torpedo-shaped anchors is investigated. A vast extent of uncertainties arises in pull-out capacity estimation due to the excessive tilt of a torpedo anchor during free-fall and subsequent embedment into the seafloor. This paper will investigate the issues encountered by the torpedo anchor during the vertical drop, which ultimately reduces the pull-out resistance. The pull-out resistance study offered by torpedo anchors is investigated using a finite element tool, PLAXIS 3D. A series of pull-out tests were conducted with anchors under four different ballast conditions (20, 40, 60 and 80%) with three chosen fin configurations (without fin, 3 fins and 4 fins). The anchors are tested for various inclinations (0°, 2.5°, 5°, 7.5° and 10°) and the effect of torpedo anchor tilt on pull-out resistance is studied, and the allowable range of anchor tilt was recommended. Thus, this study provides the benefit of ideal ballast and fins arrangements.

Keywords Torpedo anchors · Pull-out resistance · PLAXIS 3D

1 Introduction

Offshore construction requiring anchors is usually expensive and challenging. The cost of traditional anchoring systems (like drag anchors, plate anchors, piles, suction anchors and gravity structures) increases exponentially with an increase in water depth. Advanced and novel techniques of dynamically installing torpedo-shaped anchors are used nowadays to avoid external driving energy; easier, faster and simpler installation techniques; water depth independency; ability to withstand inclined load; limited use of anchor handling vessels (AHV) and remotely operated vehicles (ROVs); precise installation location positioning and needless installation time made them more economical. This most promising concept is successfully commissioned in Brazilian offshores and Goja, North Sea (Lieng et al. 2010; Medeiros 2002). These methods have been successfully used in offshore; however, there are

---

S. Keerthi Raaj (✉) · R. Sundaravadivelu · Nilanjan Saha
Indian Institute of Technology, Chennai, India
e-mail: mskraaj44@gmail.com

M. Latha Gali and P. Raghuveer Rao (eds.), *Construction in Geotechnical Engineering*, Lecture Notes in Civil Engineering 84,
https://doi.org/10.1007/978-981-15-6090-3_11

no well-established practices or design guidelines on the precise embedment depth or on the model for prediction of pull-out capacity (de Aguiar et al. 2013; Kim et al. 2015; Liu et al. 2014; Soh et al. 2015). de Aguiar et al. (2013) remarked the prediction of pull-out capacity and stress in the structure remains a great challenge. There exist uncertainties in pull-out capacity estimation due to the excessive inclination of torpedo anchor during free-fall and subsequent embedment in the seafloor. This paper will investigate the issues encountered in the verticality of the torpedo anchor, which ultimately reduce the pull-out resistance.

Researchers have noted that the influence of the tilt angle of a free-fall torpedo pile anchor on pull-out capacity is significant (Ehlers et al. 2004; Liu et al. 2014; Brandao et al. 2006). Liu et al. (2014) noted widespread usage of torpedo anchors in offshore exploration but the unpredictability related to the verticality during penetration is a major cause to affect their long-term pull-out capacity. This tilt angle leads to a reduction in estimated theoretical pull-out capacity. In the Albacora Leste field test, anchors are retrieved and redeployed due to excessive anchor tilt of more than 10° which leads to huge operational costs. Added in situ field test from Brazilian offshore reveals that always there exists a small tilt angle even after embedment due to the resistance, which affects the overall pull-out capacity. The quantitative measurement of the tilt angle and their influence on pull-out capacity was analyzed numerically using PLAXIS 3D (Brinkgreve et al. 2016), a finite element commercial package. The focus of the present study is to assess the pull-out capacity of torpedo anchors by varying the amount of ballast, number of fins and inclination configurations.

2 Anchor and Soil Properties

A typical torpedo anchor consists of a bottom nose, a ballasted trunk with fluke and pad-eye. In this study, the importance of ballasted trunk with and without a varied number of fluke is studied. The uncertainty encountered in the verticality of the torpedo anchor will reduce the pull-out resistance incorporated into the analysis. In the present study, the torpedoes used by Medeiros (2002) in field study are analyzed and validated, which has a diameter of 0.762 m, 12 m long, dry weight of 24 tonnes without a fin and also vertical fins of 0.45 m × 9 m are investigated in the study. The geometrical representation of the anchor is presented in Fig. 1a–c without and with 3 and 4 fins, respectively. The typical geometrical dimensions of the anchor with fins are shown in Fig. 1d. The included angle between the fins is 120° and 90° for 3 and 4 fins, respectively. The torpedo anchor has a conical tip with a taper angle of 30° and thickness of the fluke and ballasted trunk are 0.05 m. In the present study, the behavior of the torpedo anchor after the free-fall and embedment into the soil is considered, so the importance of hydrodynamic center and gravity center is neglected.

The shear strength profile of Campos Basin (Medeiros 2002) soil is represented by $S = 5 + 2x$, where x is a vertical distance below the ground (in meters). Pecorini and De (2015) used cohesion and frictional angle of 5 kPa and 17° to provide the

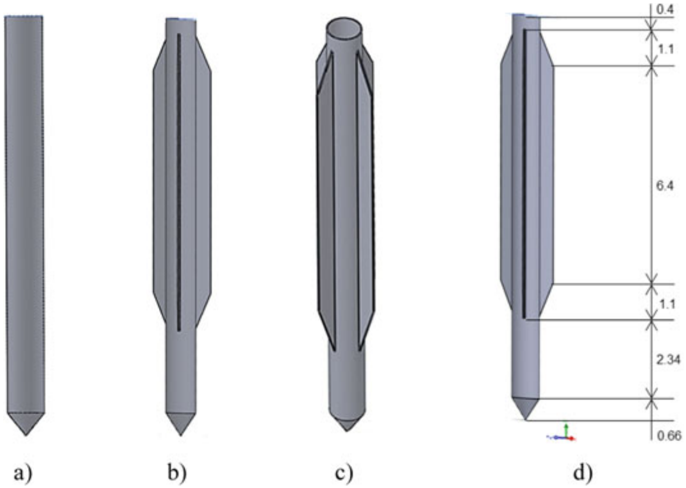


Fig. 1 Torpedo anchor **a** without fin, **b** with 3 fins, **c** with 4 fins and (4) anchor with the geometrical dimensions (all dimensions are in meters)

Table 1 Geotechnical properties of marine clay sediments and torpedo anchor

Clay sediment	
Material model	Modified Cam-Clay
Drainage type	Undrained
Cohesion, kN/m^2	5.00
Angle of internal friction, φ (°)	17
Normal consolidation line slope, λ	0.205
Swell line slope, κ	0.044
Torpedo Anchor	
Model type	Linear elastic
Unit weight of an anchor	65 kPa
Modulus of Elasticity, kN/m^2	31×10^6 kPa
Poisson's ratio	0.2
Drainage type	Non-porous

required shear strength profile with the Mohr–Coulomb model. In the present case, the modified Cam-Clay model is used to represent the same soil profile shear strength with addition stiffness property using the slope of normal consolidation line (κ) and slope of the swell line (λ). The geotechnical properties of a typical marine site with clay sediments and the corresponding torpedo anchor employed are mentioned in Table 1.

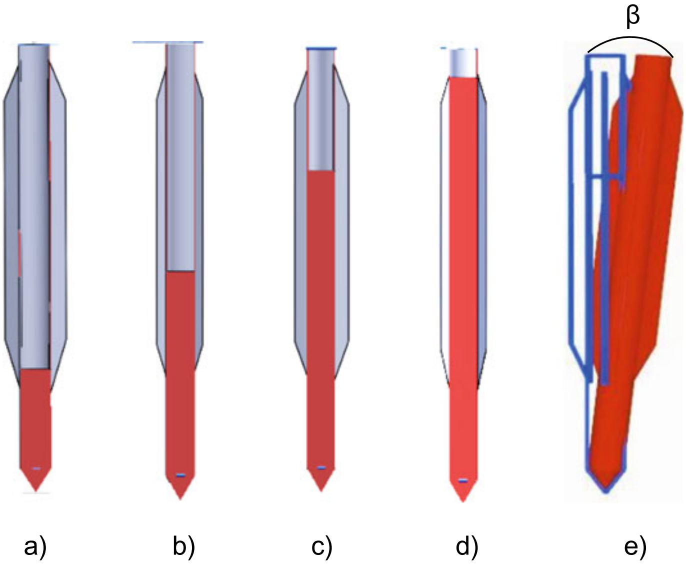


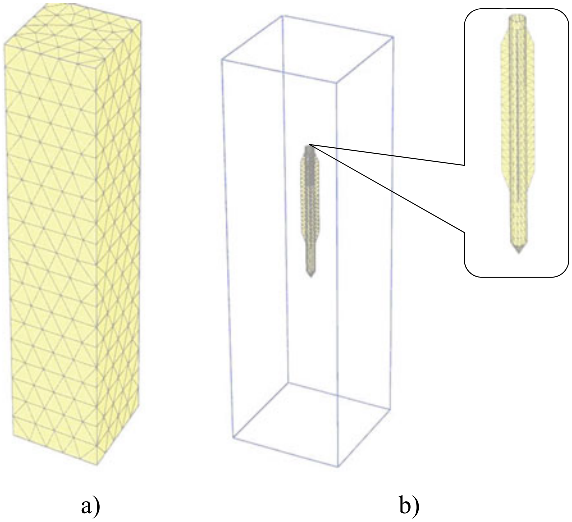
Fig. 2 Torpedo anchor with different ballast weights **a** 20%, **b** 40%, **c** 60%, **d** 80% and **e** with inclination

3 Numerical Procedures

In this set of experiments, the amount of ballast is varied in consonance with other parameters to study their influence on pull-out capacity. The parameters considered are: (i) the weight of ballast, (ii) the number of flukes and (iii) the anchor tilt angle. A series of pull-out tests are conducted with anchors under four different ballast conditions (20, 40, 60 and 80%) with three chosen fin configurations (without a fin, 3 fins and 4 fins). The anchors are tested for various inclinations ($\beta = 0°$, 2.5°, 5.0°, 7.5° and 10.0°) and the effect of anchor tilt angle on pull-out capacity is studied. Each anchor model is denoted as BxxFyIz.z. For instance, B60F4I7.5 signifies that the torpedo anchor has a ballast weight of 60% with four fins and the anchor is tested for an inclination of 7.5° about the vertical axis in the positive x-direction. In total, around 60 numerical trials are conducted and they are discussed in this paper (Fig. 2).

4 Modeling of Torpedo Anchor

PLAXIS 3D, a commercial three-dimensional finite element tool was used to perform the real-time pull-out capacity estimation. Since the torpedo-shaped anchor has a complex geometry, to compute the pull-out capacity a numerical-based finite element model is used to assess the interface between the anchor and surrounding soil. The



a) b)

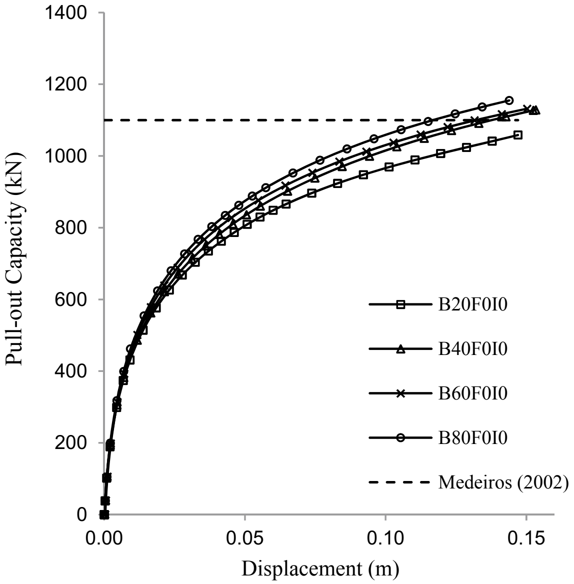
Fig. 3 Numerical representation of torpedo anchors with the surrounding soil **a** total domain and **b** torpedo anchor (detail)

3D finite element model has a length of 35 m with a square cross-section of 10 m in lateral directions as shown in Fig. 3a. The torpedo anchor is modeled first using a mesh generation algorithm and later imported into the PLAXIS 3D program. The 3D model torpedo anchor possesses a diameter of 0.762 m and 12 m long, which is embedded in the soil domain (see Fig. 3b). The embedded 3D torpedo anchor is assumed as a rigid body, which has a negligible change in shape during operations (i.e., deformations during the entry/pull-out is neglected). This assumption is based on the fact that the stiffness of the torpedo is large compared to the stiffness of the soil. The rigid body motion is expressed in terms of translation and rotation. Here, the translation corresponds to tensile load application direction and rotation corresponds to the tilt of the torpedo anchor, respectively.

5 Validation

A full-scale field test is conducted by Medeiros (2002) in the Campos Basin, with 0.762 m torpedo piles and medium tip penetration of 20 m. The torpedo anchors offered a pull-out capacity of 1100 kN while applying a tensile load in a horizontal direction. The same condition is modeled in PLAXIS 3D, and the typical load–displacement curve is shown in Fig. 4. From Fig. 4, for 80% ballast weight the ultimate pull-out capacity is 1154 kN. The obtained results from the present simulation are close to the field observations. The difference in the field and the numerical result is about 4.6% and thus, the PLAXIS 3D numerical model can represent the full-scale field results. Consequently, for 20, 40 and 60% ballast condition the ultimate pull-out resistance are 1058, 1126 and 1131 kN, respectively, and the difference is within a

Fig. 4 Validation—pull-out resistance of finless torpedo anchor



permissible 5%. From Fig. 4, it is also noted that with an increase in ballast weight, the pull-out capacity of the anchor increases.

6 Results and Discussion

The deformed mesh and tilted torpedo anchor models are presented in Fig. 5a, b. de Sousa et al. (2010) studied the failure mechanism of the torpedo anchor in a cohesive soil and observed that for horizontal loading, there is a mobilization of large soil mass before the collapse followed by subsequent plastic deformation. The same type of failure is observed while applying the tensile load in the lateral direction as depicted in Fig. 5b, where large mobilization of soil around the torpedo anchor is evident. In this section, the effect of the tilt angle, number of fins and ballast weight are discussed in detail.

6.1 *Effect of the Tilt Angle*

Figure 6 indicates the typical load–displacement curve for various tilt angles for four-finned torpedo anchors with 40% ballast conditions. It is clearly observed that for an increase in tilt angle there is a gradual reduction in the pull-out capacity. For a torpedo anchor without any initial inclination (i.e., perfectly embedded vertically

Fig. 5 **a** 3D deformed torpedo anchor **b** deformed mesh slice

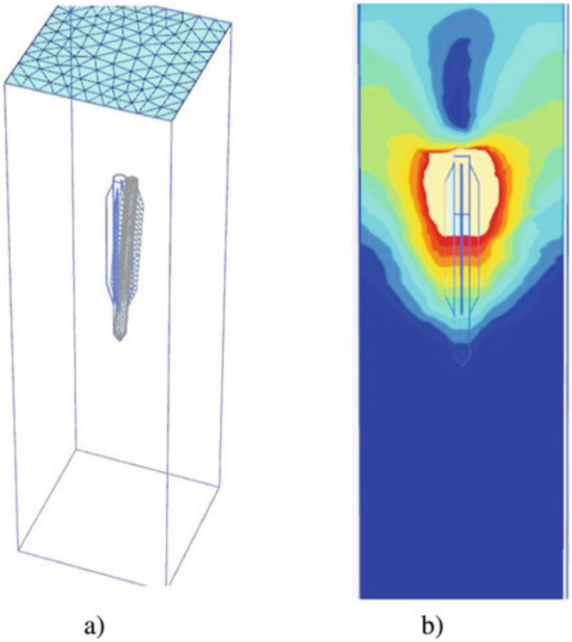
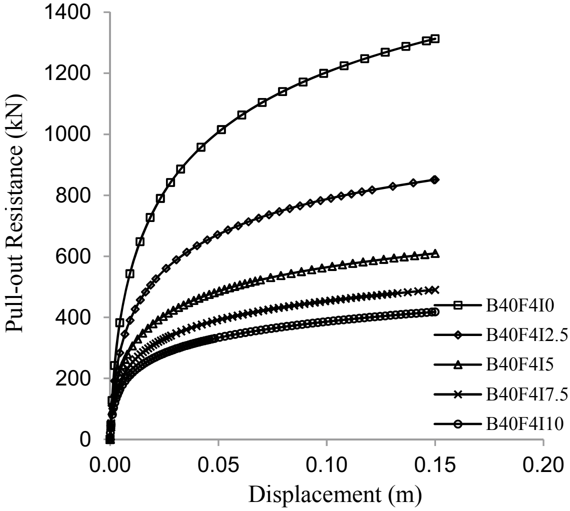
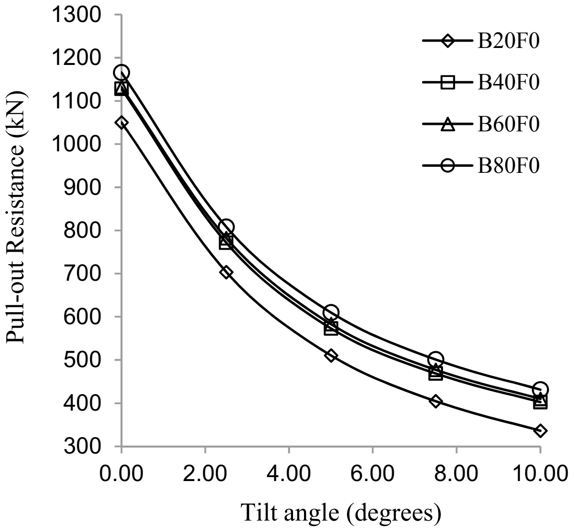


Fig. 6 Effect of the tilt angle



in the subsoil domain), the pull-out capacity is maximum. With an increase in tilt angle from 0° to 10°, the pull-out capacity drops from 1313 to 418 kN. The reduction in pull-out capacity is 35, 53, 63 and 68% for 2.5°, 5°, 7.5° and 10°, respectively. Therefore, the torpedo anchors with lesser tilt angle are stable and have an efficient pull-out capacity. For a more stable anchor the tilt should be less than 2.5°, even

Fig. 7 Effect of ballast weight



which at 2.5° the capacity is reduced by 35%. Hence, precise installation technique should be adopted for achieving lesser anchor tilt; otherwise even small tilt angles may cause substantially reduced pull-out capacity.

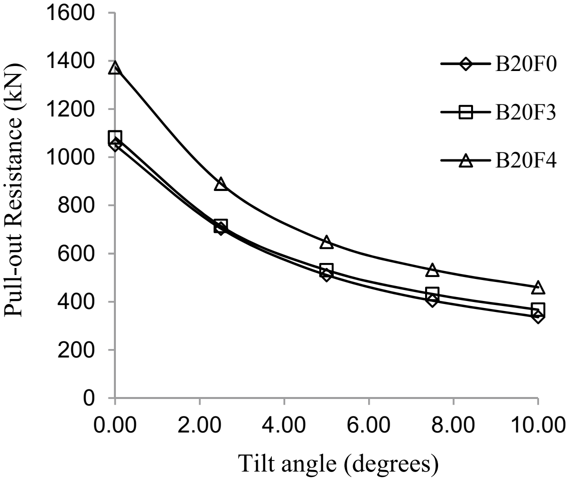
6.2 *Effect of Ballast Weight*

Figure 7 shows the typical load–displacement curve for different percentages of ballast conditions for finless torpedo anchor with zero inclination conditions. From the figure, one observes that with an increase in the percentage of ballast weight there is a gradual increase in the pull-out capacity. For a torpedo anchor with 80% ballast weight the pull-out capacity is maximum. With an increase in tilt angle from 0° to 10°, the pull-out capacity drops for all the ballast conditions. The reduction in pull-out capacity is about 31, 48, 57 and 63% for 2.5°, 5°, 7.5° and 10°, respectively, for 80% ballast weight. Therefore, the torpedo anchors with more ballast weight are more stable and have a maximum pull-out capacity. Hence, an anchor with larger scrap weight should be used for achieving more penetration depth and pull-out capacity.

6.3 *Effect of the Number of Fins*

Figure 8 represents the typical load–displacement curve for various finned torpedo anchor with 20% ballast conditions. One observes that for an increase in the number of fins there is a gradual increase in the pull-out capacity. For a torpedo anchor

Fig. 8 Effect of number of fins



without any fin, the pull-out capacity is minimum. The pull-out capacity drops for all the fin conditions, with an increase in tilt angle from 0° to 10°. The reduction in pull-out capacity is 35, 53, 61 and 65% for 2.5°, 5°, 7.5° and 10°, respectively, for four-finned torpedo anchor. Therefore, the torpedo anchors with more number of fins are stable and have the additional pull-out capacity. The stability of torpedo anchors is increased with an increased number of fins since they offer extra lateral stability to the anchor. Hence, extra fins not only help during free-fall but also in achieving additional stability in a pull-out stage, though they offer lesser embedment depth during anchor penetration in the subsoil.

7 Conclusion

This paper attempts a comprehensive study in analyzing the various design parameters of torpedo anchor, viz., the number of fins, the effect of tilt angle and the amount of ballast on the pull-out capacity. The soil is assumed to be marine clay sediment having properties of Indian offshore. The torpedo anchors are assumed to be made of linearly elastic material. The numerical results are validated through the established full-scale field results (Medeiros 2002), and the potential advantages of ideal ballast and fins arrangements with the goal of maximum ultimate capacity are discussed. The conclusions of the present study are:

i. The torpedo anchors with lesser tilt angle are stable and have an efficient pull-out capacity. A stable anchor should have the tilt angle within 2.5°.

ii. The torpedo anchors with more ballast weight are stable and have a larger pull-out capacity.
iii. The stability of torpedo anchors increases with an increased number of fins since they offer extra lateral stability to the anchor.
iv. The torpedo anchors with lesser tilt angle, more ballast weight, with fin are more stable and observed to offer maximum pull-out resistance.

Acknowledgments The first author gratefully acknowledges the support from the Ministry of Human Resources and Development, Government of India through Indian Institute of Technology Madras, Chennai. The author also thanks the Department of Ocean Engineering and the Department of Civil Engineering of IIT Madras for the research facilities.

References

Brandao FEN, Henriques CCD, Araujo JB, Ferreira OCG, dos Santos Amaral C (2006) Albacora leste field development- FPSO P-50 mooring system concept and installation. In: Proceedings of offshore technology. Offshore Technology Conference. Texas U.S.A. https://doi.org/10.4043/18243-ms

Brinkgreve RBJ, Swolfs WM, Engine E (2016) PLAXIS user's manual, PLAXIS bv, The Netherlands

de Aguiar CS, de Sousa JM, Sagrilo LS, Ellwanger GB, Porto EC (2013) a simple approach for determining the holding capacity of torpedo anchors embedded in cohesive soils. Proc Int Conf Offshore Mech Arctic Eng. https://doi.org/10.1115/OMAE2013-10809

de Sousa JM, de Aguiar CS, Ellwanger GB, Porto EC, Foppa D, de Medeiros CJ (2010) Undrained load capacity of torpedo anchors embedded in cohesive soils. ASME Proc Jo Offshore Mech Arctic Eng 133(2) (2010). https://doi.org/10.1115/1.4001953

Ehlers CJ, Young AG, Chen J (2004) Technology assessment of deepwater anchors. In: Proceedings of 36th annual offshore technology conference, offshore technology conference, Houston, Texas, Paper No. OTC 16840 (2004)

Kim YH, Hossain MS, Wang D, Randolph MF (2015) Numerical investigation of dynamic installation of torpedo anchors in clay. Ocean Eng 108:820–832. https://doi.org/10.1016/j.oceaneng.2015.08.033

Lieng JT, Tjelta TI, Skaugset K (2010) Installation of two prototype deep penetrating anchors at the Goja Field in the North Sea. In: Proceedings of the 2010 offshore technology conference, paper OTC 20758

Liu XD, Sun JJ, Yi JT, Lee FH, Gu HH, Chow YK (2014) Physical and numerical modeling of the performance of dynamically installed anchors in clay. ASME. Int Conf Offshore Mech Arctic Eng 1A: Offshore Technology. https://doi.org/10.1115/omae2014-23769

Medeiros CJ (2002) Low cost anchor system for flexible risers in deep waters. In: Proceedings of offshore technology. Offshore Technology Conference. Texas U.S.A. https://doi.org/10.4043/14151-ms

Pecorini D, De A (2015) Pull-out capacity analysis of offshore torpedo anchors using finite-element analysis. In: Proceedings of international society of offshore and polar engineers, Hawaii, USA. ISSN 1098-6189

Soh BP, Pao W, Al-Kayiem HH (2015) Numerical analyses for improved hydrodynamics of deep water torpedo anchor. In: Proceedings of IOP conference series: material science engineering, 100. https://doi.org/10.1088/1757-899x/100/1/012059