# THIXOTROPIC PROPERTIES OF DEEPWATER INDIAN MARINE CLAYS FROM EASTERN OFFSHORE – EVALUATION AND CORRELATIONS

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**Abstract.** Thixotropy of clays is an important parameter in offshore geotechnical engineering. Thixotropy is responsible for the short term gain in undrained shear strength of clays after remolding and hence it is imperative to incorporate it in the analysis while estimating the short-term load carrying capacity of foundation systems at varying time after their installation. Different clays display different thixotropic properties and so far, there has been negligible information available about Indian offshore clays. Hence, this paper presents and discusses the thixotropic properties of eastern offshore deep water clays measured during a recent geotechnical investigation.

The paper discusses different factors which affect the thixotropic behavior of clays along with the investigations done and reported in literature to correlate thixotropy with other soil parameters such as plasticity index, liquidity index, water content etc. Further, a comparison is presented between the eastern Indian offshore thixotropy data with the published data from other parts of the world. Evaluation of possibility of development of some correlation(s) for Indian offshore thixotropy data has also been presented.

**Keywords:** Thixotropy , Offshore, Geotechnical, Deep water, Clays

## 1 Introduction

The determination of undrained shear strength of clays is important for design of foundations for any structural system interacting with clays. There are numerous parameters which influence the shear strength at a given time e.g. at undisturbed state, remolded state immediately after installation of foundations and at a state after some time – post-foundation installation. One such property is thixotropy which is of considerable importance in offshore geotechnical engineering defining the strength gain after installation of foundations in clays in short term.

Thixotropy is defined as “a process of softening caused by remolding which is an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume, whereby a material stiffens while at rest and softens or liquefies upon remoulding” (Mitchell 1960). The measure of thixotropy is the ratio (called the thixotropy strength ratio) between the shear strength at a given time after thixotropic strength gain and the shear strength just after remolding.

Thixotropic properties are different for different clays and there has been no information available about Indian offshore clays. Hence the study presented in this paper was performed to get an insight into the thixotropic property of clays, particularly in the deep-water Indian Marine Clays from Eastern offshore. The data used for this study is from a recent deep water project of ONGC. In the present paper, comparison and subsequent evaluation of the eastern Indian offshore thixotropy data with the published data from other parts of the world is made and possibility of development of some correlation(s) for Indian offshore thixotropy data has also been examined.

## 2 Literature survey

From literature search it appears that the published material on thixotropy is very limited. It also appears that thixotropic property of clays was noticed quite early in the history of geotechnical engineering practice. As early as 1948, Moretto (1948) reported study on the thixotropic behavior of natural clays.

### 2.1 Effect of mineralogy

Skempton and Northey (1952) presented data for pure mineral clays – Kaolinite, Illite and Bentonite and some natural clays, using the laboratory vane. Kaolin clay showed almost no thixotropy, Illite showed comparatively more thixotropic gain and Bentonite showed comparatively large strength gain (and continued to gain strength even after a year). It was hence surmised that mineralogy plays an important part in the thixotropic behavior of clays.

### 2.2 Effect of plasticity characteristics

Santos-Soage (2011) studied the factors affecting thixotropic behavior of clays and found that the factors which affect the consistency limits (Atterberg limits) of clays also affect the thixotropic behavior. Hence, clay microstructure, mineralogy, electrolyte concentration, organic content etc., which are reflected in the Atterberg limits, also affect the thixotropy of clays.

### 2.3 Effect of water content

Skempton and Northey (1952) indicated that water content of the clay has influence on the thixotropic strength gain. They concluded that thixotropic strength gain decreases with decrease in water content below liquid limit and, thixotropic strength gain may be negligible at or close to the plastic limit. In their study they used water content in terms of liquidity index.

### 2.4 Thixotropy relationship with sensitivity

Yang and Andersen (2016) also investigated relation between sensitivity and thixotropy strength ratio. It was observed that a trend of increasing thixotropy strength ratio with sensitivity can be seen but it appears to level-off at higher time intervals (beyond 1 day) and sensitivity of 5.

## 3 The data used in the present study

The published data used for the present study has been taken primarily from Yang and Andersen (2016). To a limited extent data presented by Colliat (2015) has also been considered. The reason for choosing data primarily from Yang and Andersen (2016) was that it is for marine clays (including also data from some Indian marine clays); is comparatively substantial and, is in easily usable form. These data were then compared with the data from recently concluded geotechnical investigation of ONGC Eastern offshore deepwater project.

### 3.1 Published data

**Data from Yang and Andersen (2016)**
The database used by Yang and Andersen (2016) contained thixotropy data for marine clays from 15 offshore sites in Norway, Ghana, Angola, Egypt, India, and Malaysia. The database has a very good range of various geotechnical parameters as shown in Table 1.

**Table 1.** Range of basic parameters in the database (Yang and Anderson-2006 )

| Basic Parameters | Marine Clays |
|---|---|
| Water Content,% | 21-145 |
| Plasticity Index ,$I_{P,\%}$ | 19-97 |
| Clay Fraction,% | 28-80 |
| Sensitivity | 1.5-10 |
| OCR | 1-4.5 |

**Data from Colliat (2015).**
Colliat (2015) presents thixotropy data from 22 sites from offshore Guinea (Gulf of Guinea) and Colliat et al. (2010) present the geotechnical data for the Gulf of Guinea clays in details. The water depth ranged between 350 m to more than 1400 m. The water content at most of the sites ranges between 80 to 150%. The soils display very high plasticity index – ranging typically between 70 and 130%. The range of sensitivity is from 3 to 6. Mineralogical examination showed Kaolinite as the dominant mineral and Smectite also as a significant portion.

### 3.2 Eastern Indian deepwater offshore data

**Data from Eastern Indian offshore soil.**

The data pertains to a recent deepwater Eastern Indian offshore project of ONGC. Soft to firm clays were encountered at most places to considerable depth below seafloor. Thixotropy is measured in terms of thixotropy strength ratio: ratio between the shear strength after a time after thixotropic strength gain and the shear strength just after remolding. The strength test used is laboratory vane. The strength test of a number of samples of remolded clay is done immediately after remoulding. The samples are then stored in a way that the water content remains the same as original sample. The tests were again performed at time intervals of 0. 1, 2, 4, 7, 14, 30 and 60 days. The thixotropy test results were available from 11 borings in the area. The water depth ranged from ~30 m to 1240 m. The sample depth (below seafloor) range (where the thixotropy data were available) was from 3.6 to 47.4 m. The clays are highly plastic clays and generally have very high clay fraction reaching up to 100%. The water content ranged from 53 to 101 % and plasticity index ranged from 43 to 88. OCR best estimates varied from 0.65 to 1.8. The sensitivity ranged from 2 to 3. No mineralogical composition study is available however, inferred from Activity data, the soils are generally believed to be composed of Illite or a combination of Illite and Montmorillonite.

## 4 Data analysis and results

Primarily, the data from Yang and Andersen (2016) and, to much lesser extent data from Colliat (2015) have been used to compare the eastern Indian offshore data.

The literature search resulted in getting comparatively limited data. However, the data from Yang and Andersen (2016) was found to be suitable for the study purpose. Colliat (2015) and Colliat et al. (2010) did not present the data values and hence could not be directly incorporated in the study.

Yang and Andersen (2016) had also checked thixotropy strength ratio against Activity and Plasticity Index but the plots showed very high scatter without any clearly discernible trend. Inclusion of Indian data also did not improve the situation and hence these plots are not included in this paper.

### 4.1 Comparison of data from Yang and Andersen (2016) and eastern Indian Offshore marine clays for use in the study

Before evaluating the Indian data against published data, the data from Yang and Andersen (2016) and from Eastern Indian offshore were comapred to examine the compatibility and usabilit**y.** Three basic differences were noticed :

- It can be seen that the time intervals at which the strength is measured are different for eastern Indian offshore and Yang and Andersen (2016) paper. The common time intervals for thixotropy strength testing are 1, 30 and 60 days and, direct comparison of data is only possible for data for these time intervals.

- It was noted that the thixotropy tests and sensitivity tests in Yang and Andersen (2016) data are all from fall cone tests while in eastern Indian offshore project laboratory vane tests were used.
- Yang and Andersen (2016) state that their database contains only those test results where the change (decrease) in water content over the duration of the test-set was less than 1.5% of the original water content. Examination of the eastern Indian offshore data showed maximum variation of water content in most of the tests of 3 to 5%. Only a few tests show variation less than 1.5 or 2%.

It is to be noted that an increase of water content will tend to reduce the shear strength and vice versa. It was realized that the quantification of variation of shear strength due to these differences is not possible to do realistically. Also due to limited amount of data available from Eastern Indian Offshore project, it would not havebeen practical to use data only from tests where the water content variation is less than 1.5% as is the case in Yang and Andersen (2016) database. It was hence decided to go ahead with further study and evaluate the results subsequently.

Also, Yang and Andersen (2016) use liquidity index (LI) as one of the correlating parameter. During an earlier study done at ONGC (IEOT, 2002), it was observed that the intrinsic state parameter, $w/w_L$ i.e. ratio of natural water content and liquid limit (Nagaraj and Miura, 2001) correlates extremely well with LI:

$$LI = 1.81.w/w_L - 0.81 \quad (1)$$

(n = 841, $R^2$ = 0.95 and Standard Deviation = 0.09)

It is also noticed that the former parameter is much simpler and eliminates the arbitrariness of plastic limit definition and determination (Nagaraj and Miura, 2001, Ghanekar et al., 2010). Since data from Yang and Andersen (2016) were also available for deriving the intrinsic state parameter, this parameter was used instead of liquidity index.

Since intrinsic state parameter also normalizes the water content, it was not considered worthwhile to separately investigate relationship between water content and thixotropy strength ratio.

### 4.2 Thixotropy strength ratio versus intrinsic state parameter

Figure 1 to Figure 3 presents the relationship between intrinsic state parameter and thixotropy strength ratio using Indian offshore data plotted along with data from Yang and Andersen (2016) for 1 day, 30 days and 60 days intervals respectively.

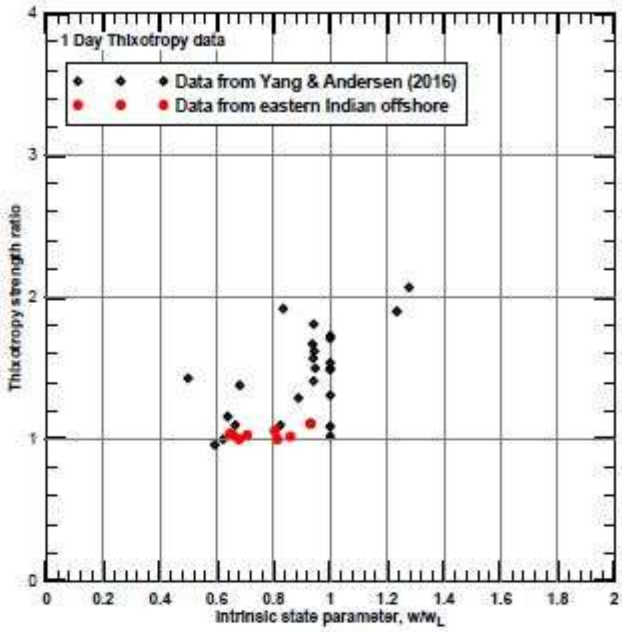


**Fig. 1.** Thixotropy strength ratio versus Intrinsic state parameter – 1 day interval

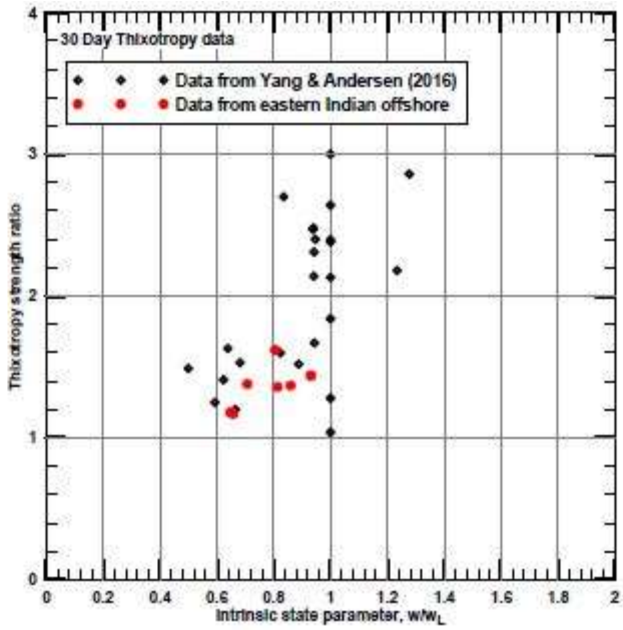


**Fig. 2.** Thixotropy strength ratio versus Intrinsic state parameter – 30 day interval

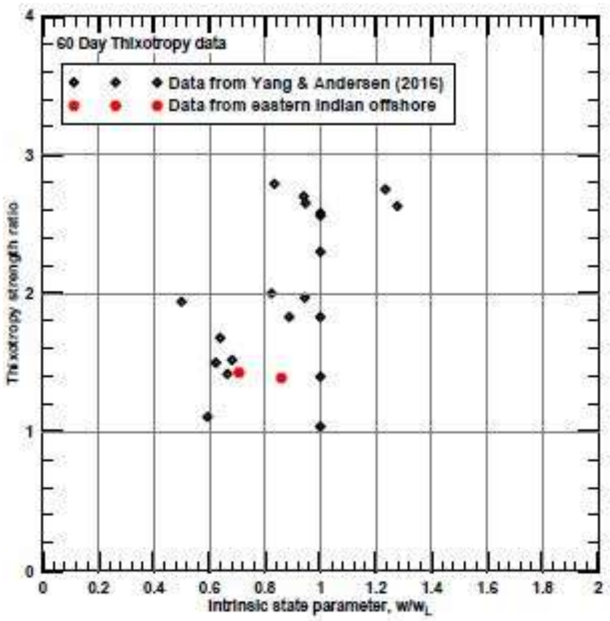


**Fig. 3.** Thixotropy strength ratio versus Intrinsic state parameter – 60 day interval

### 4.3 Thixotropy strength ratio versus sensitivity

Figure 4 to Figure 6 presents relationship between sensitivity and thixotropy strength ratio using Indian offshore data plotted along with data from Yang and Andersen (2016) for 1 day, 30 days and 60 days intervals respectively.

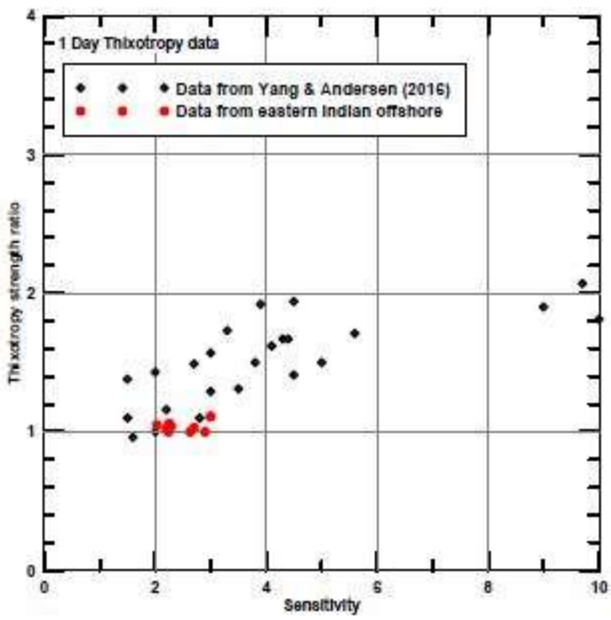

**Fig. 4.** Thixotropy strength ratio versus Sensitivity– 1 day interval

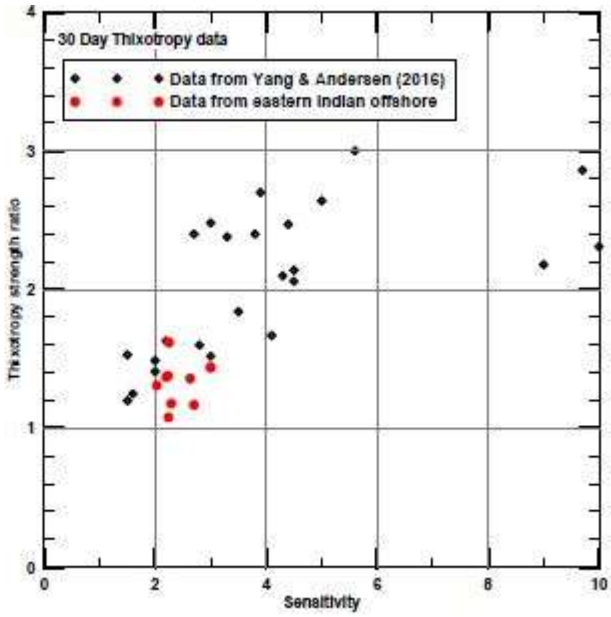


**Fig. 5.** Thixotropy strength ratio versus Sensitivity– 30 day interval

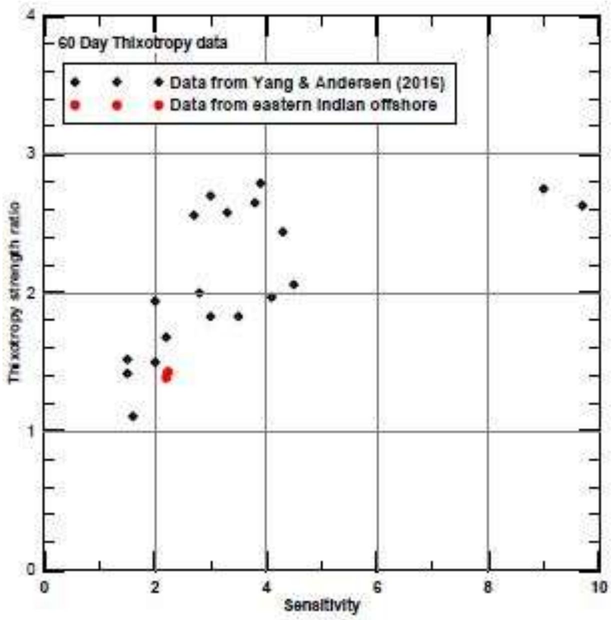

**Fig. 6.** Thixotropy strength ratio versus Sensitivity–60 day interval

### 4.4 Thixotropy strength ratio versus time

Figure 7 presents thixotropy strength ratio versus time in logarithmic scale. The figure plots the data from eastern Indian deepwater offshore along with ranges of data presented by Yang and Andersen (2016) and Colliat (2015).

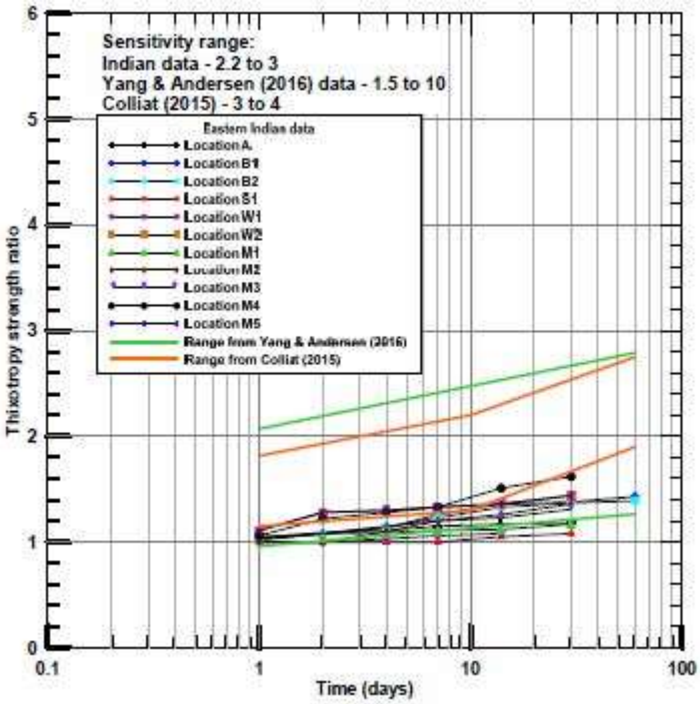


**Fig. 7.** Thixotropy strength ratio versus time

### 4.5 Sensitivity versus Intrinsic state parameter

Bjerrum (1954) has proposed a correlation between liquidity index (LI) and sensitivity (St) as follows:

$$St = 10(0.15+0.73.LI) \quad (2)$$

As stated earlier, a very good correlation was found between liquidity index and intrinsic state parameter (IEOT, 2002). Hence it was decided to investigate the relation between intrinsic state parameter and sensitivity.

Figure 8 presents relationship between intrinsic state parameter and sensitivity using Indian offshore data plotted along with data from Yang and Andersen (2016). An attempt was made to develop a correlation between sensitivity and intrinsic state parameter. The best correlation is exponential and is shown on the figure. The correlation is not very strong with coefficient of determination, $R^2$ equal to 0.66. For comparison, correlation proposed by Bjerrum (1954) for Norwegian clays is also presented on Figure 8 by converting LI to $W/W_L$.

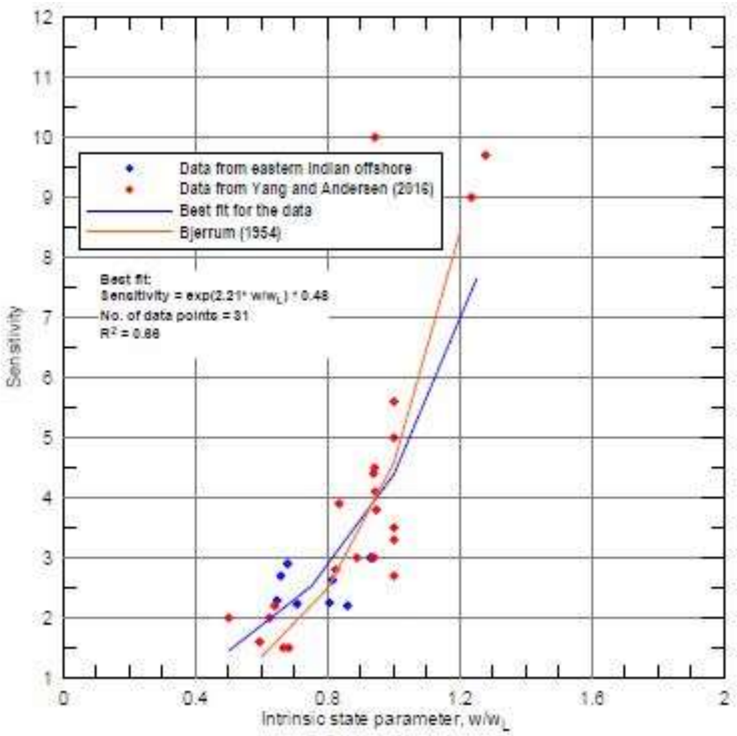


**Fig. 8.** Sensitivity versus Intrinsic state parameter

## 5 Discussion of results and recommendations

The thixotropy data from eastern Indian offshore was compared with data from Yang and Andersen (2016) for the relationships with intrinsic state parameter and sensitivity. Time versus thixotropy strength ratio was also compared with data from Yang and Andersen (2016) and, Colliat (2015).

### 5.1 Thixotropy strength ratio versus intrinsic state parameter and sensitivity

The data, for the two comparisons, could only be examined for 1 day, 30 days and 60 days intervals.

Despite differences in the testing method and variation of water content during the tests, the eastern Indian data neatly plots within or close to the range of data presented by Yang and Andersen (2016) – for thixotropy strength ratio versus intrinsic state parameter or sensitivity (refer Figure 1 to Figure 6 ). A difference can also be gleaned from the plots that that the ranges for Intrinsic state parameter and sensitivity is much lower for eastern Indian offshore as compared to Yang and Andersen (2016) data.

It is also seen that due to the scatter in data, only trends can be discerned (especially for 30 days interval) and, it is not worthwhile to try to develop correlations. In general, it can be stated at present that the thixotropy strength ratio increases with increasing intrinsic state parameter and sensitivity, confirming the trends reported in literature.

### 5.2 Thixotropy strength ratio versus time

From Figure 7, it can be seen that eastern Indian offshore data plots toward the lower side of the range reported by Yang and Andersen (2016) and Colliat (2015). This generally matches with range of sensitivity of the two datasets and variation of thixotropy strength ratio with sensitivity. Although the lower bound of the range of sensitivity of Yang and Andersen data is lower than the Indian data, some of the curves from Indian data plot below the lower bound range of Yang and Andersen (2016) data. The reason is not very clear. In the absence of definitive data about mineralogy and activity, it is not possible to evaluate or analyze the data further.

### 5.3 Sensitivity versus Intrinsic state parameter

The relation between liquidity index and sensitivity is well known in literature. Yang and Andersen (2016) had also presented the relation using their database. Figure 8 shows their data superimposed with data from eastern Indian offshore but using the intrinsic state parameter instead of liquidity index. The eastern Indian data neatly plots in the range shown by Yang and Andersen (2016). A clear trend of increasing sensitivity with intrinsic state parameter is observed which is also supported by Bjerrum (1954) data as presented in the figure.

## 6 Conclusion

The study presented in the paper gives an insight into the thixotropic behaviour of eastern Indian offshore deepwater clays.

It was observed after a thorough literature review that the published material on thixotropy is very limited. However, it is noted that mineralogy, plasticity characteristics and water content have an influence on the thixotropic behavior of clays.

Further, there exists some relationship between sensitivity and thixotropy. The investigations done by researchers reveal that for sensitivity values less than about 5, an increasing trend is seen between thixotropy and sensitivity which Indian data conforms to, as found in this study.

To evaluate and examine whether some correlations can be developed for Indian offshore deepwater data, the data from recently concluded deepwater geotechnical investigation for ONGC's Eastern Indian Offshore field was compared with data taken primarily from Yang and Andersen (2016) and to some extent the data presented by Colliat (2015). It was found that the data trends from eastern Indian deepwater offshore conform to the data trends presented in literature for clays encountered world over. However due to considerable scatter in data and data limitations, only trends could be discerned and correlations could not be developed.

Comparison of thixotropy strength ratio with intrinsic state parameter (an equivalent parameter to liquidity index but simpler and more rational) and sensitivity also confirmed the fact that the thixotropy strength ratio increases with increasing intrinsic state parameter and sensitivity.

## 7 Acknowledgement

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