International Journal of Physical Modelling in Geotechnics

Physical modelling in Geotechnical Earthquake Engineering

--Manuscript Draft--

Manuscript Number:	IJPMG-D-14-00033R1
Full Title:	Physical modelling in Geotechnical Earthquake Engineering
Article Type:	ICPMG Session Reports
Corresponding Author:	Gopal Santana Phani Madabhushi, Ph.D University of Cambridge Cambridge, UNITED KINGDOM
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Cambridge
Corresponding Author's Secondary Institution:	
First Author:	Gopal Santana Phani Madabhushi, Ph.D
First Author Secondary Information:	
Order of Authors:	Gopal Santana Phani Madabhushi, Ph.D
Order of Authors Secondary Information:	
Abstract:	Physical modelling plays an important role in Geotechnical Earthquake Engineering. It is used to understand failure mechanisms and study the dynamic behaviour of a wide variety of dynamic problems with earthquake and other dynamic loading. As in the previous ICPMG conferences, Perth conference also attracted a good number of papers on this important topic. This session report briefly describes the contributions from different papers.

Physical modelling in Geotechnical Earthquake Engineering – 2: Session Report

Gopal Madabhushi
Professor of Civil Engineering & Director, Schofield Centre,
University of Cambridge, UK

1 Introduction

Centrifuge modelling has played an important role in investigating a wide variety of geotechnical earthquake engineering problems. In successive international physical modelling conferences the number of papers that are presented on the topic of earthquake engineering have increased. The ICPMG2014 conference at Perth was no exception. Further, in addition to the earthquake engineering topic other civil engineering problems in which dynamic loading plays an important role are also being studied using physical modelling. For example, the problem of dynamic loading on a bridge pier due to ship impact has been investigated by Viswanadham et al (2014).

In this session report 13 papers will be considered that were presented in this area. However, there were more papers in geotechnical earthquake engineering that used centrifuge modelling, but were classified in different sessions of the conference such as shallow foundations (e.g. Heron et al, 2014) or deep foundations (e.g. Haskell et al, 2014).

In this session report the overall distribution of the papers will be considered next. This will be followed by a brief description of the key note lecture and short reports on individual papers in the session. For further details on any of the papers, the readers are encouraged to see the full papers. The session report will conclude by identifying some of the future trends as well as research challenges and future needs in the area of earthquake geotechnical engineering.

2 Distribution of papers

The research topics covered by geotechnical earthquake engineering are vast both in terms of the boundary value problems that were investigated and the range of developments in physical modelling that were reported in this session. There were two sessions in this area at the ICPMG 2014 conference called ‘Earthquake engineering – 1 & 2’. Papers in the first session were reported by Prof Anastasopoulos of University of Dundee. In this report papers from the second session are considered. Table 1 classifies the 13 papers that were in this session titled ‘Earthquake engineering - 2’ co-chaired by the author and Prof Bruce Kutter of University of California, Davis. Apart from the keynote lecture on centrifuge modelling of the seismic behaviour of stone architectural heritage buildings delivered by Prof Kim of KAIST and the session report, four other papers were selected for oral presentation during the conference.

All 13 papers will be considered in this session report. As explained in the introduction to this report, there were other papers in this conference that also dealt with earthquake engineering problems but were presented in different sessions such as Shallow foundations or Pile Foundations. These papers will be considered by the relevant session reporters.

Table 1: Distribution of papers organised based on the topic of research

	Title of the paper	Authors	Country	Broad area of the paper
Historical structures	Centrifuge modelling on seismic behaviour of stone architectural heritages (Keynote lecture)	Kim DS & Park HJ	South Korea	Historic and Heritage Structures
Shallow Foundations	Seismic soil structure interaction: a parametric study on shallow foundations	Escoffier S & Chazelas, JL	France	Shallow foundations in dry sand: SSI problem
	Effects of ground motion intensity parameters on soil-foundation-structure-interaction and site response	Ghayoomi M and Dashti S	USA	Shallow foundations in dry sand: SSI problem
	Centrifuge modelling of seismic liquefaction effects on adjacent shallow foundations	Marques A.S.P.S. & Coelho P.A.L.F. Haigh S.K. & S.P.G. Madabhushi	Portugal/UK	Shallow foundations: Soil Liquefaction
	Effect of liquefaction duration on ground progressive failure under 2-D biased load	Ishikawa, A, Shamoto, Y, Mano, H, Zhou YG, Liang T & Li YG	Japan	Shallow foundations: Soil Liquefaction: Progressive failure
Landslides	Centrifuge modelling of earthquake-induced submarine landslide and its gravity flow transition	H. Takahashi, S. Sassa & Y. Morikawa	Japan	Soil liquefaction – submarine slope failure
Pile foundations	Seismic performance of pile foundation with reinforcement of steel sheet-piles in sand	Zhang X & Takemura J	Japan	Pile foundations: SSI
	Stiffness matching of model reinforced concrete for centrifuge modelling of soil-structure interaction	Al Defae A.H. & Knappett J.A.	UK	Pile foundations: sloping ground
Input motions	Use of Ricker wavelet ground motions as an alternative to push-over testing	M. Loli& I., Anastasopoulos, J.A. Knappett & M.J. Brown	Greece/UK	Facilities development
1-g testing	1-g shaking table tests on mitigation of seismic subsidence of structures	R. Rasouli & I. Towhata T. Hayashida	Japan	Laboratory scale testing
	Shaking table testing of retrofitted 3-storey building	I. Anastasopoulos, V. Drosos & N. Antonaki	Greece	Laboratory scale testing
	Seismic earth pressure reduction on gravity retaining walls using EPS geo-foam	Dasaka SM, Dave TN Gade VK & Chauhan VB	India	Laboratory testing
Impact testing	Centrifuge model tests on the measurement of impact energy on bridge pier foundations embedded in sand	Viswanadham BVS, Guha A, Sudarshan BV, Kundu, S & Bhattacharjee D	India	Facilities development: Centrifuge testing:

3 Description of individual papers

The session began with a keynote lecture delivered by Prof D-S Kim followed by the session report and four individual paper presentations.

3.1 Centrifuge modelling of seismic behaviour of historic stone structures

The keynote lecture in this session was on evaluating the seismic behaviour of stone structures of historic and cultural significance. This is a very novel research which was focussed on investigating the seismic behaviour of stone architectural heritage buildings in South Korea using physical modelling. Centrifuge models that are accurate scale models of the prototype pagodas were produced at different scale factors. One such model and the prototype stone pagoda are seen in Fig. 1. Modelling of models was utilised to show that accurate capture of the seismic behaviour of the stone structures was achieved.

Figure 1 somewhere here

The results of this investigation showed that centrifuge modelling can be used to investigate the seismic behaviour of stone structures where both friction between the stone blocks and the rocking of the whole structure with gaps opening between individual blocks play a key role in determining the overall dynamic response. Detailed results obtained by the authors can be seen in the full paper, which is part of the conference proceedings. There is a need to understand and mitigate seismic risk to many Cultural and Heritage buildings and monuments in Europe and worldwide, e.g. Italy, Greece, Spain and Portugal and India/China etc.

3.2 Shallow Foundations

Seismic behaviour of shallow foundations continues to be an area of interest to many centrifuge modellers. Under this section there were four papers as indicated in Table 1. Two of the papers focussed on soil-structure interaction between the shallow foundation and the dry soil. The other two papers considered liquefaction effects. As mentioned before there were other papers in this area (e.g. Heron et al, 2014) that were placed in different sessions.

3.2.1 Dry soil beds

Escoffier and Chazelas (2014) considered a simple shallow foundation on a dry sand bed. This research was part of the SERIES project and is complementary to the work reported by Heron et al, 2014. The moment-rotation loops were plotted for the shallow foundations as shown in Fig.2. The change in the slope and size of these plots for small and large earthquakes was investigated. These indicate the stiffness and damping that was mobilised in the soil for these earthquakes. The relative density of the soil and bearing pressure exerted by the foundations were the variables considered in this research. Compared to the Cambridge study, this research extended to much larger bearing pressures of 300 kPa.

Figure 2 somewhere here

The second paper in this area was by Ghayoomi and Dashti (2014). In this paper the focus was on characterising the ground motion based on centrifuge testing carried out on a two-storied model structure. The authors advocate use of a two parameter based system rather than simple peak ground acceleration (PGA) to characterise ground motions used in dynamic centrifuge modelling. The two parameters proposed were Arias intensity and shaking intensity rate (SIR). The general point of this paper was to emphasise the importance of considering both the amplitude and the frequency content of ground motions.

3.2.2 Liquefaction problems

Two papers that considered liquefaction effects on shallow foundations were included in this session. Marques et al (2014) investigated the settlement of two shallow foundations that are in close proximity when the foundation soil liquefies. The two foundations considered exerted different bearing pressures. Excessive settlements were observed for both the light and heavy foundations. During settlement of these foundations, the soil is subjected to monotonic shearing which resulted in a reduction in the excess pore pressures in the soil directly underneath the foundations.

Ishikawa et al (2014) investigated the post-liquefaction behaviour of L shaped buildings on shallow foundations. The aim of this research was to investigate the progressive failure of the foundations post-liquefaction and the consequent evolution of rotations of the foundations. Two different types of sands namely the Fujian and silica sands were tested. The main result of this research was the comparison of the rotations suffered by the foundations and duration for which the soil remained liquefied.

3.3 Landslides

There was only one paper that investigated seismic slope stability in this session. Takahashi et al (2014) investigated the submarine landslides following earthquake loading. The main objective of this research was to investigate the transition of landslides into gravity flows following liquefaction of slopes. The authors investigate the effect of fines content in the soil on the run-off distance after slope failure. They term this as 'flowability' of the slope.

3.4 Pile foundations

There were two papers in this session that are related to centrifuge modelling of pile foundations. As mentioned before there were other papers in this area (e.g. Haskell et al, 2014) that were placed in different sessions.

Al-defae and Knappett (2014) considered the inclusion of pile foundations in a slope as part of a stabilisation scheme to mitigate the slope failure following earthquake loading. The model piles that were made from aluminium alloy were compared to model RC piles. The latter can develop cracks following slope movements and give the researchers the ability to study the post-cracking behaviour of piles inserted into slopes.

Zhang and Takemura (2014) compared the performance of piled foundations with skirted pile foundations. The model sections are shown in Fig.3. Based on the centrifuge test results the authors show that inclusion of sheet piles around an existing pile foundation can significantly improve the seismic performance of the piled foundation. This research has a practical relevance in high density built environment, where there is limited space available around an existing building. This method can be used to improve the foundations and reduce the seismic vulnerability of the building. This research won the 'best paper award' at the conference.

Figure 3 somewhere here

3.5 Application of dynamic loading

There were two papers in this session that focused on the type of dynamic loading that was used in centrifuge testing. These could be considered as development of facilities to conduct dynamic tests.

3.5.1 Input motion to simulate push-over tests

Often push-over tests are conducted in centrifuge models using hydraulic or pneumatic actuators. Loli et al (2014) used the Ricker wavelet to simulate push-over type loading on a foundation using the servo-hydraulic shaker. They tested foundations of two different sizes. The Ricker wavelet allows a direct comparison between the loading applied via the shaker and an actuator driven push-over. This is a novel application of the servo-hydraulic shaker and this paper was selected as one of the best papers.

3.5.2 Impact loading

Another paper in this area was by Viswanadham et al (2014) that describes the development of equipment to apply impact loading. Ship impact on bridge piers and other problems are gaining importance. This paper describes a multiple ball dropping system that can simulate impact loading on bridge piers embedded in a dry sand bed. The decrease of accelerations with increasing radial distance was studied in this research. The authors could have included a theoretical basis to their observations as one would expect a cubic function of decay in impact energy with the radial distance.

3.6 Laboratory based 1-g testing

There were three papers in this session that reported on laboratory based physical modelling. 1-g testing can give good insight into the basic mechanisms at play and these papers report results from well conducted experiments.

Rasouli et al (2014) describe shaking table tests that were conducted to investigate the efficacy of sheet pile walls in reducing building settlements following ground liquefaction. They tested continuous sheet pile walls as well as discontinuous walls. They also investigated the role of lowering of ground water table in reducing the settlements due to soil liquefaction. As expected the continuous sheet pile results in a significant reduction in the building settlements. In the case of discontinuous sheet piling, the soil once liquefied was able to flow through the slots and therefore the building continued to settle. It must be pointed out that if this research was carried out in a centrifuge, the higher stresses may result in a stronger dilation as the liquefied soil tries to flow through the discontinuous sheet piling.

Anastaspoulos et al (2014) carried out relatively small scale laboratory tests on portal frames with soil foundations. They tested 3 storied model structures in the laboratory on a shaking table. The foundation soil layer was 500 mm deep. The idea of this research was to investigate the use of under-designed foundations that may act as fuses during strong shaking. Their experimental results show that the under-designed foundations suffer rocking motions and hence reduce the storey drift in the upper floors of the model building.

Dasaka et al (2014) also used laboratory based shaking table testing of small scale models to investigate the use of geo-foam in reducing the thrust generated on retaining walls due to earthquake loading and application of a surcharge on the backfill. The authors present the variation of earth pressure with depth behind the retaining wall, but it is not clear whether these earth pressures were directly measured or back calculated from load cell reading.

4 Emerging Areas

The research into liquefaction phenomena and their effects on various civil engineering infrastructure continues to be an area of strong growth. There are many more centrifuge centres around the world that have acquired earthquake actuators and hence liquefaction research and geotechnical earthquake engineering in general will continue to grow. As highlighted by the keynote lecture of this session, an emerging area of research will be the seismic vulnerability assessment of historical and cultural buildings using centrifuge modelling. This type of research has not been extensive thus far as protection of human life by making buildings earthquake-resistant has been the main focus of research. This thinking is now shifting and understanding the seismic behaviour of ancient structures of historic importance or buildings that have cultural relevance is gaining impetus. This is particularly true for many historic buildings in many southern European countries like Italy, Greece etc. as well as those in developing world like in India, China, Mexico etc. Investigating the seismic behaviour of such structures brings in additional challenges. Creating small scale model buildings that accurately capture the salient features of these structures requires careful thought. From a research point of view, the sliding and rocking of individual stone blocks, opening of gaps between the blocks can limit the transmission of ground motions and hence the lateral loads imposed on the superstructure. However, the interfaces between the blocks must be modelled carefully to capture the roughness, any lack of fit and workmanship in the original structure.

Successful modelling of these structures at a small scale using centrifuge modelling can also help us evaluate different retrofit schemes that are proposed to reduce the seismic vulnerability of historic structures or even 20^{th} century structures that were constructed before modern codes were implemented. For example, use of internal or external reinforcement, additional internal supports or use of resins to bond individual stone blocks can all be tested to determine their effects on the dynamic response of these structures. Modifications to foundation soil to improve the seismic performance of these structures is another area that has not been investigated thus far and again centrifuge modelling can play an important role.

The New Zealand earthquakes near Christchurch in 2010 and 2011 resulted in a change of thinking in earthquake engineering. Prevention of collapse of structures and protecting human lives is no longer the only goal of earthquake engineering. Minimising the damage both to the structural components as well as superficial elements such as facades, building services etc. during a strong event are also important. Quick repair and reusability of structures in the aftermath of an earthquake are becoming more important. Again with carefully thought out model making techniques, centrifuge modelling can help us make important contributions in this area.

5 Research challenges and future needs

There are some challenges that are arising while attempting dynamic centrifuge modelling. Previous constraints on fast data acquisition systems and earthquake actuators are fast disappearing with advances in digital computing and improved control systems, Madabhushi (2014). However, increased sophistication is required in terms of centrifuge model making especially when modelling structural systems to study soil-structure interaction. Developments in 3-D printing can help in this regard.

From a geotechnical point of view, measurement of dynamic earth pressures still remains challenging. While use of miniature earth pressure cells continues, there are uncertainties regarding the relative stiffness between pressure cells and the soil in which they are placed. Generally measuring earth pressure next to a stiff inclusion is easier. Again development of tactile pressure pads that can measure dynamic earth pressures is anticipated to play a major role in this area. Similarly use of high speed digital imaging to carryout of PIV analyses on earthquake problems is gaining impetus.

In terms of measurement of accelerations, the advent of cheap MEMS accelerometers has taken off and the number of instruments is no longer limited due to cost constraints. However, use of these MEMS accelerometers in saturated models needs careful thought in terms of sealing and careful studies need to be conducted on how well these devices couple with the saturated soil, particularly as soil starts to lose its stiffness owing to excess pore pressure generation. Rotation of the devices is also a problem in this scenario, as MEMS devices tend to pick up not only the lateral accelerations but a component of the centrifuge acceleration as they rotate. While acceleration measurement has improved, measurement of pore pressures is still expensive. There is an urgent need to develop MEMS based pore pressure measurement devices that are cheap and robust. Similarly there is a need to have similar MEMS based strain gauge measurement systems.

References

Al-Defae AH and Knappett JA (2014) Stiffness matching of model reinforced concrete for centrifuge modelling of soil-structure interaction. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1067-1072.

Anastaspoulos I, Drosos V and Antonaki N (2014) Shaking table testing of retrofitted 3-storey building. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1031-1037.

Dasaka SM, Dave, TN, Gade VK and Chauhan VB (2014) Seismic earth pressure reduction on gravity retaining walls using EPS geo-foam. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1025-1030.

Escoffier S and Chazelas J L (2014) Seismic soil structure interaction: a parametric study on shallow foundations. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1045-1051.

Ghayoomi M and Dashti S (2014) Effects of ground motion intensity parameters on soil-foundation-structure-interaction and site response. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1017-1023.

Haskell JJM, Madabhushi SPG and Cubrinovski M (2014) Effect of pile spacing on pile demand for small pile groups in laterally spreading soil. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 737-742.

Heron CM, Haigh SK and Madabhushi, SPG, (2014) Isolating shallow foundations from seismic loading, *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 1, pp. 621-627.

Ishikawa A, Shamoto Y, Mano, H, Zhou, YG, Liang T. and Li YG (2014) Effect of liquefaction duration on ground progressive failure under 2-D biased load. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1079-1085.

Kim D-S and Park, HJ (2014) Centrifuge modelling on seismic behaviour of stone architectural heritages. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 1, pp. 47-60.

Loli M, Anastaspoulos I, Knappett, JA and Brown, MJ (2014) Use of Ricker wavelet ground motion as an alternative to push-over testing. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1073-1078.

Madabhushi, SPG (2014) Centrifuge modelling for civil engineers. Taylor & Francis, London. ISBN 9780415668248.

Marques ASPS, Coelho PALF, Haigh SK and Madabhushi SPG (2014) Centrifuge modelling of seismic liquefaction on adjacent shallow foundations. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1039-1044.

Rasouli R, Towhata I and Hayashida T (2014) 1-g shaking table tests on mitigation of seismic subsidence of structures. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1001-1007.

Takahashi H, Sassa S and Morikawa Y (2014) Centrifuge modelling of earthquake-induced submarine landslide and its gravity flow transition. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1009-1015.

Viswanadham BVS, Guha A, Sudarshan, BV, Kundu S and Bhattacharjee D (2014) Centrifuge model tests on the measurement of impact energy on bridge pier foundation embedded in sand. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1061-1066.

Zhang X and Takemura J (2014) Seismic performance of pile foundation with reinforcement of steel sheet-piles in sand. In. *Proc. 8th International Conf. on Physical Modelling in Geotechnics* – ICPMG 2014 (Gaudin & White (eds)). CRC Press, Leiden, the Netherlands, vol. 2, pp. 1053-1059.

Figure Captions:

Figure 1 Prototype stone pagoda and the centrifuge model

Figure 2 Moment-rotation loops

Figure 3 Model pile foundations and skirted pile foundations

Figure-1
Click here to download high resolution image

Figure-2

Click here to download high resolution image

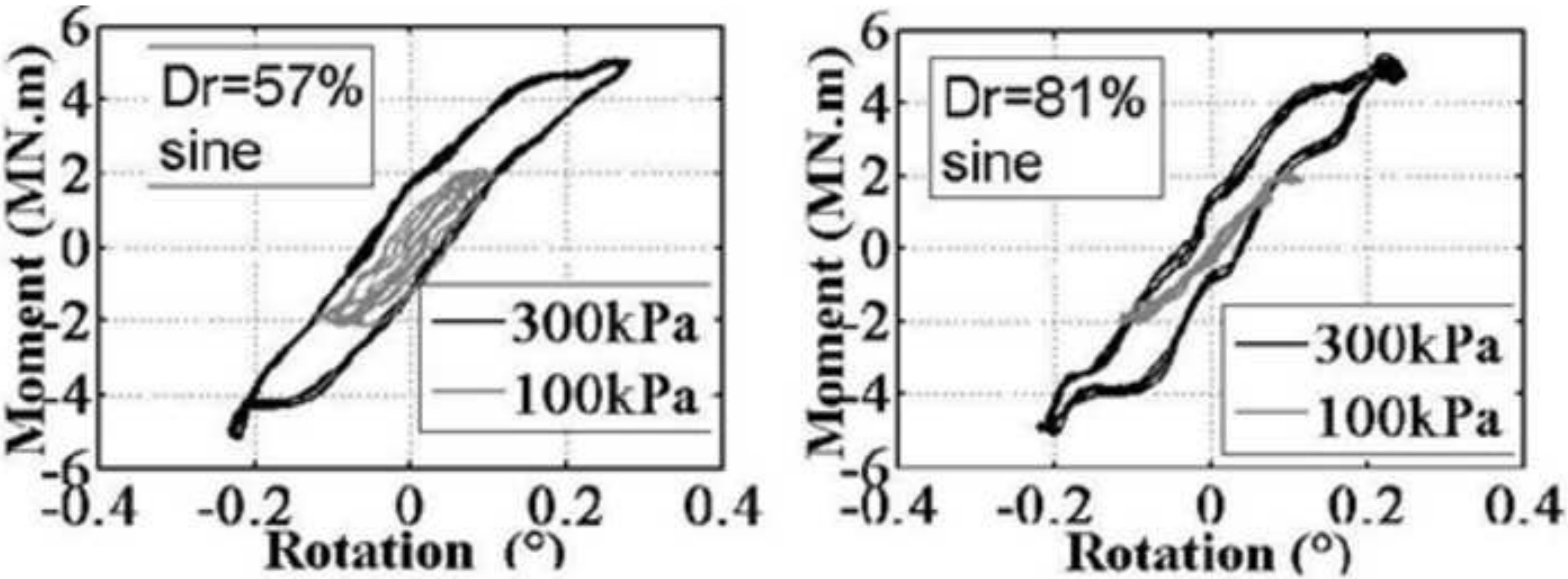

Figure-3
Click here to download high resolution image