A FIELD TESTING RESEARCH ON THE CHARACTERISTICS OF NEGATIVE SKIN FRICTION ALONG PILE CAUSED BY SEISMIC SUBSIDENCE OF LOESS

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ABSTRACT :

Now pile foundation is widely used in the earthquake-prone loess area of China. However, negative skin friction (NSF) along piles induced by a sudden settlement of loess during strong earthquakes, seismic subsidence, has not been taken into account in design of pile foundation due to the lack of NSF data related to field testing. In order to research NSF along piles in loess ground during seismic subsidence and develop a method to estimate this seismic NSF, the authors perform a field test at a loess site (Q_3) by means of a series of explosion (a short delay blasting), in which two piles of 20m long are grouted. The expected ground motion created by the explosions is strong enough to induce an obvious seismic subsidence in the field. There are 40 stress gages to be disposed into the two piles in average with a certain interval, 2m, to collect the data of NSF with depth during the field testing. The whole field observation continues 11 days. In this testing, the maximum NSF reaches 86kPa at the buried depth of 13m, with an average NSF of 54kPa on pile, which is much greater than before in-situ data of NSF related to loess settlement by soaking. It could be obviously revealed that, furthermore, NSF increases with the depth along pile gradually and there is an extreme value of NSF along pile, likely be the maximum value also, near/at the neutral point, where NSF is equal to zero due to absence of relative displacement between pile and soil mass; during the explosions and immediately after it, NSF increases rapidly with loess seismic subsidence, whereas in the subsequent stages, the development of NSF becomes slow and slow.

KEYWORDS: Field testing, pile foundation, negative skin friction, stress gage, loess, seismic subsidence

1. INTRODUCTION

Loess is a particular kind of soil with porous structure and weak cohesion, depositing in different stages of the Quaternary. The compressibility of loess mass is low at natural moisture content as a result of a special microstructure (Miao Tiande, 2001). While water immerges, however, strength of loess mass will be reduced dramatically, which could make this soil collapse (Gao Guorui, 1980; Yang Yunlai, 1988; Rogers et al., 1994; and Feda, 1996). In China, area of loess reaches 640,000 km^2, in which collapsible loess area is about 500,000 km^2 (Wang Guolie et al., 2001). Furthermore, most loess area in China is also seismic region, where many strong earthquakes occurred. Under the effect of moderate or strong earthquakes, liquefaction or seismic subsidence of loess is easily induced. These three kinds of subsidence due to collapse, liquefaction and seismic subsidence of loess, which relate to immerging water, additional load or ground shock respectively, could come into being negative skin friction (NSF) along piles, which badly endangers pile foundation.

NSF is a complicated problem and it connects with some other theoretical problems in soil mechanics area. Because in-situ test costs a lot and also needs a long-time period to prepare and accomplish, existing test data is limited for meeting the needs of NSF study. Especially, research data related to NSF on pile in loess ground caused by seismic subsidence, which is a rapid residual strain of soil mass induced by an enough dynamic stress, such as an earthquake, is very rare. As a result, NSF along piles generated by a suddenly seismic subsidence in loess ground during strong earthquakes can not been taken account into the design of piles foundation, whereas piles foundation is widely used in the earthquake-prone loess area of China at present.

In order to investigate the characteristics of NSF along piles in loess ground during seismic subsidence induced by earthquakes and develop a method to estimate the seismic NSF, the authors performed a field testing at a loess site (Q_3) by means of a series of explosions, a short delay blasting, on September 12, 2006. In this paper, details related to field test design, observatory data and relevant analysis results are presented.

2. DESIGN OF THE FIELD EXPLOSION TEST

2.1. Observation Field

Having a flat topography, a proper thickness of collapsible loess deposit and a certain distance away from villages, the field at Lijiawan village in Gansu province of China is suitable to carry out the explosion testing on NSF along piles induced by seismic subsidence of loess ground. Sedimentary sequence of this field can be roughly seen at terrace's basset. Data obtained by exploratory well, two hand digging holes both with a 28m depth, shows that from top to bottom there are four layers overlaying Tertiary red bed, including arable layer, seismic loess, redeposited loess, and pebble bed. With a buried depth of 1m and a 14m thickness, the upper loess layer has the typical physical characteristics of collapsible loess, i.e. loosen soil mass, high porosity, and great void ratio. In this layer, water content of soil ranges from 12% to 16% and slight clay particle is in sight at some position. The characteristics of redeposited loess, with a thickness of 13m, differs from its overlain soil by that water content of soil is roughly less than 10% and clay content is much more. Horizontal bedding, furthermore, is distinctly visible in this soil layer and it increases gradually with the depth. The laboratory test shows that the residual strain, coefficient of seismic subsidence, of the loess layer with the depth 16m and 20m is mighty less than the upper soil mass during a moderate or strong dynamic stress; this situation accords with the strata sequence of observation field.

2.2. Design of a Short Delay Blasting and Testing Piles

There are two reinforced concrete piles, as showed in Fig. 1, to be laid in the loess ground. Considering in-situ test cost and the above-mentioned characteristics of residual strain, the two test piles are seated on the soil layer with buried depth of 22m. Seating on a non-seismic subsidence layer, each of the two piles with a diameter of 0.8m is 20m long (Fig. 2). In their body, 40 stress gages are disposed in average with an interval of 2m along the direction of depth. For each pile the gages arrange as a symmetrical pair to eliminate the eccentric force and the two axial planes of gages in piles cross cut each other. Before detonating, an adjustment for dynamic strain instrument shows that all gages is in good condition and have a high sensitivity to respond external force.

As corresponding points of explosives plotted on the field surface, the 30 shot points, with an interval of 3.14m, are disposed along a circularity, whose diameter is 30m and centre is situated at the center of the test site. During blasting process each shot detonates two explosives at the same time, which are symmetrical against the centre of testing site. There are three kinds of delay time, 655ms, 705ms and 760ms, to be selected for the short delay blasting, and combining the delay time after each shot, expected duration of ground motion should reach 10.7s.

3. DEVELOPING PROCESS OF NSF ALONG PILES AFTER EXPLOSIONS

3.1. Characteristics of Seismic Subsidence of Loess in the Field

Observation data shows that all points developed an obvious subsidence in the test site. During the whole period of this field testing, minimum and maximum seismic subsidence of loess ground in testing site is about 13mm and 33mm, and the maximum point stands at the south of the field. On the other hand, maximum seismic subsidence of soils around the site reaches 26mm, whereas minimum seismic subsidence in this region is about 0mm. After explosions, the development of loess seismic subsidence becomes slow and slow. Curves of seismic subsidence versus time as shown in Fig. 3 indicate that development of seismic subsidence submits an exponential function and the variation characteristic of settlement increment is similar to the developing process of seismic subsidence and it could be distinctly discovered that those observation points with more seismic subsidence likely have a higher increasing rate of settlement than other points.

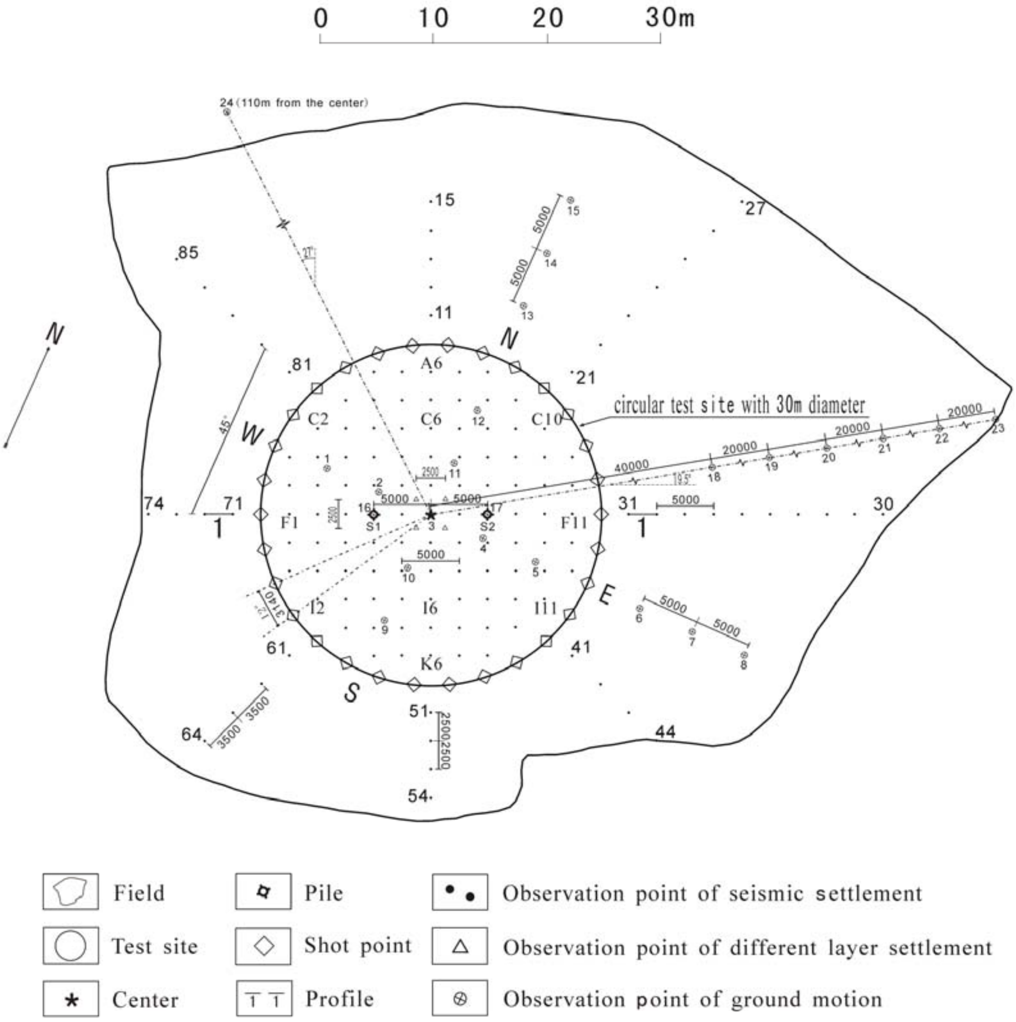


Fig. 1 Details of all kinds of observation point

3.2. Distribution of NSF along Piles

Distribution of NSF along pile with depth and its developing process during period of field testing are presented in the Fig. 4 It can be interpreted by actual contribution of effective weight to NSF during seismic subsidence of each soil layer that there is no only one extreme value of NSF on pile with depth. By an envelope line for the NSF curves, the situation of several extreme values as shown in Fig. 4 will be able to simplify and this fact will be obvious that NSF increases with the depth along pile gradually.

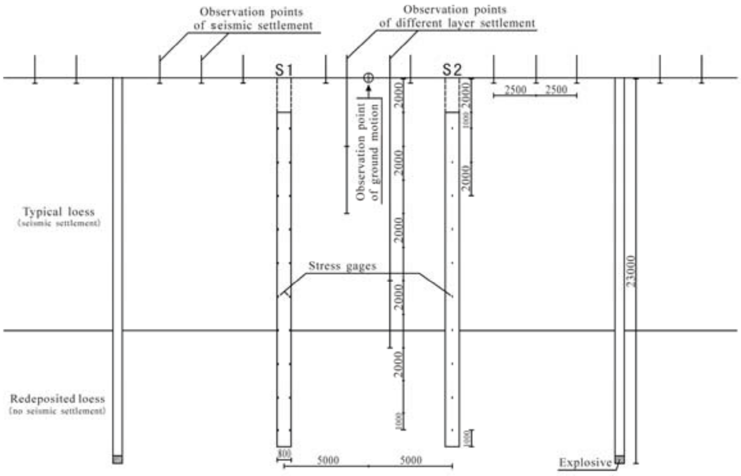


Fig. 2 Profile of testing disposal in the field

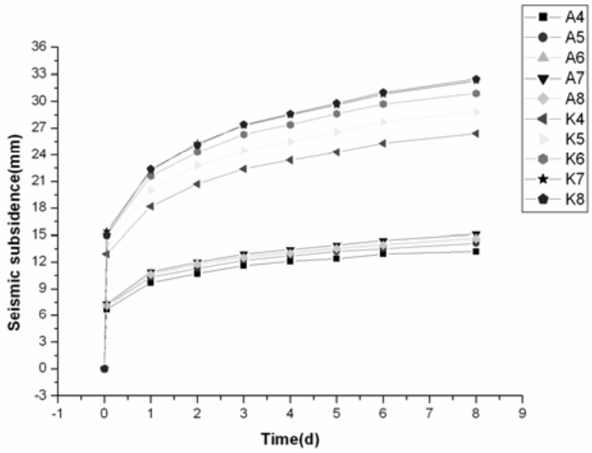


Fig. 3 Development of loess seismic subsidence, where A4~A8 and K4~K8 express the northmost and the southmost observation points respectively

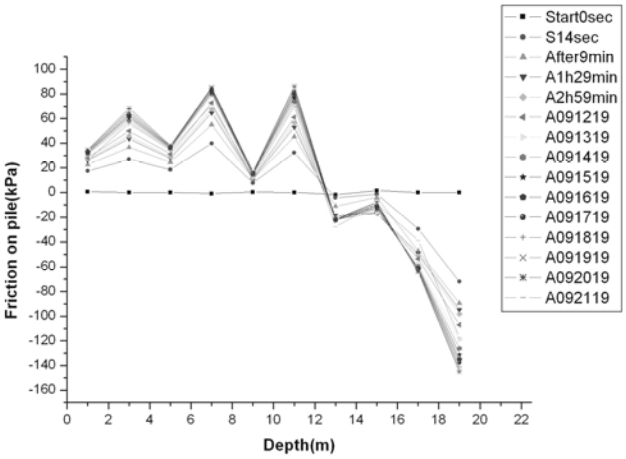


Fig. 4 Distribution of NSF along pile, in which Start0sec denotes the detonating moment, A is an abbreviation from after the explosion test and 091219 figures the month/day/time

Hence there is an extreme value of NSF along pile, likely be the maximum value also, near/at the neutral point, where NSF is equal to zero due to absence of relative displacement between pile and soil mass. During the whole field testing, moreover, the position of neutral point is almost at the same depth, approximately a 13m depth of pile body or a corresponding depth-buried of 15m, which accords with the bottom depth of seismic loess layer in the testing field. These situations of NSF's extreme value along pile and position change of neutral point, which could be the evidences to reveal seismic NSF observed by authors here related to the static friction, differ from a typical characteristic of NSF related to loess subsidence by soaking (Sun Junjie et al., 2003; Sun Junjie et al., 2006).

During this field testing, maximum value of NSF attains to 86kPa at the 11m depth of pile body, i.e. a buried depth of 13m; average NSF reaches 54kPa and the corresponding total NSF is about 1654kN. This observation magnitude along pile in seismic subsiding loess ground is much greater than NSF on pile in collapsing loess field.

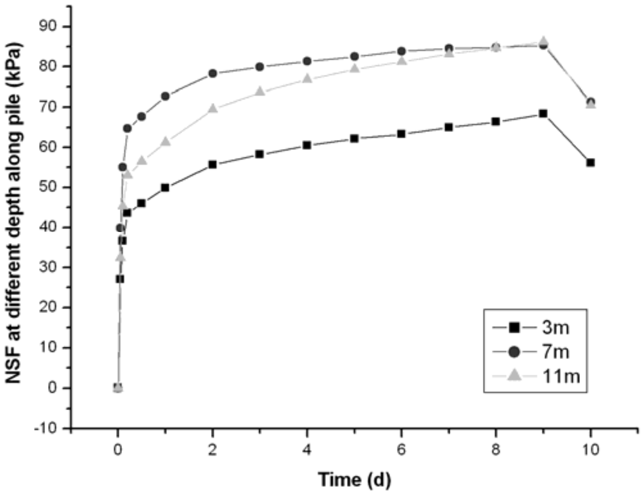
3.3. Developing characteristics of NSF

Fig. 5 describes that during period of explosion and immediately after it, NSF along pile increases rapidly related to seismic subsidence by means of a series of explosion. In other stage after explosions, the above-mentioned development of NSF on pile becomes tardy and tardy. Variation characteristics of NSF along pile with depth at different observation time are greatly similar each other in the field testing. After the explosions immediately, the maximum NSF along pile is about 40kPa (Tab. 1), in this situation with an average value of 24kPa on pile, whereas this value reaches 86kPa at the end of observation, with a 54kPa average value. Therefore, the maximum NSF along pile increases more than one time, and average value on pile enhances a similar factor also (86/40 and 54/24). Compared the above-mentioned increasing rate of NSF with the before-mentioned increment process of loess seismic subsidence, it could be revealed that NSF along pile is proportional to seismic subsidence of loess. This result is a tangible proof for that settlement of soil mass around pile should be one of the key factors to influence NSF along pile (Sun Junjie et al., 2006).

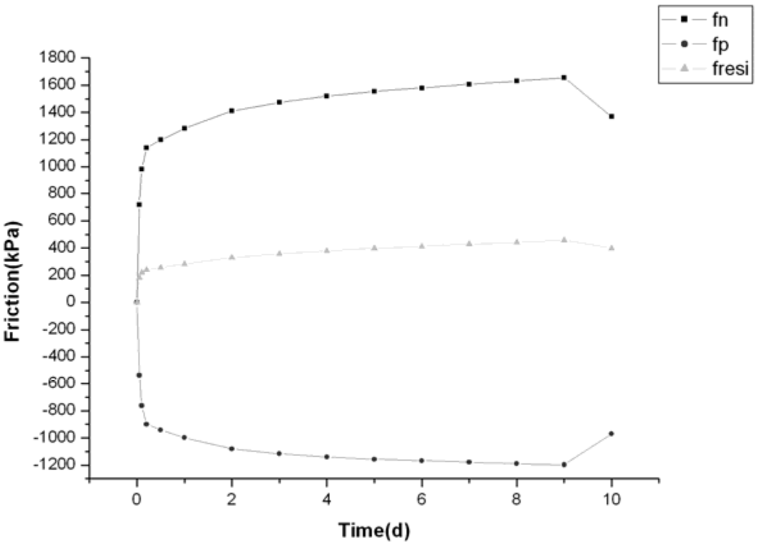
Tab. 1 Extreme value of NSF along pile, 2006091212 expressing the year/month/day/hour

Time		NSF at three depths of pile body (kPa)		
		3.0 m	7.0 m	11.0 m
2006091212 (detonating time)	immediately	27.00	39.83	32.37
	9min	36.68	55.06	45.24
	1h29min	43.59	64.71	53.03
	2h59min	46.01	67.72	56.53
2006091219		49.88	72.75	61.19
2006091319		55.59	78.28	69.46
2006091419		58.22	79.97	73.64
2006091519		60.46	81.33	76.79
2006091619		62.15	82.51	79.34
2006091719		63.26	83.83	81.19
2006091819		65.02	84.52	83.12
2006091919		66.32	84.83	84.68
2006092019		68.36	85.32	86.13
NSF ratio of immediately to 2006092019 (%)		39.5	46.7	37.6

In Fig. 5(a), the developing process of NSF at three depth along pile, especially the process at 11m depth, could reveals some particular characteristics of NSF induced by a less seismic subsidence of loess field. On the 9th day after explosions, NSF at 11m depth along pile becomes greater than NSF at 7m depth, whereas before this day, the former is less than the latter (Tab. 1). This phenomenon shows that the developing process of NSF reported by authors here is a gradual change from top to bottom in the soil layers. NSF and positive skin friction (PSF) have a similar process in this explosion testing (Fig. 5(b)). Here total NSF attains 1654kN and total PSF is about 1197kN. Residual NSF, 457kPa, subtracting total PSF from total NSF, should be balanced by soil mass beneath pile tip.



(a)



(b)

Fig. 5 Developing process of friction along pile with time, in which the sudden drawdown after 9 days considered with a dynamic test for the attenuation of stress induced by a weight dropper in pile body: (a), extreme NSF at different depth of pile body with time; (b), total friction on pile with time, fn, fp, and fresi expressing the total NSF, the total positive skin friction (PSF), and the difference between the NSF and PSF, respectively

3.4. Relationship between NSF and seismic subsidence of loess

Seismic subsidence of loess is an abrupt subsidence of loess ground due to seismic loading in non-saturated and low moisture condition (Wang Lanmin, 2003). The observation data of seismic subsidence in loess field reported here proves that this abrupt progress of soil subsidence is authentically existent. Contrasted to the transitory process of explosions, however, development of loess seismic subsidence is a relative slow-motion.
Lost gravitational potential energy of subsiding soil mass and shear strength of soil are the dominating factors to generate NSF along pile; it is not the key factors that why and how settlement of soil mass takes place (Sun Junjie et al., 2006). Combining Fig. 3 and Fig. 5, it is obvious that developing processes of loess seismic subsidence and NSF along pile during this test field have a similar characteristic, and this feature consequently reveals that NSF along pile is proportional to seismic subsidence of loess.

In each pile body, gages are disposed by a symmetrical way. Therefore, it is possible to distinguish the friction on different side of pile, such as E side-W side or S side-N side. As a result, Fig. 6 describes friction (NSF and PSF) condition along different sides of piles. For pile S1, NSF along its W side is greater than E side, and the difference reaches 20kPa; on the other hand, NSF along pile S2's N side is less than its S side, and the maximum difference is about 10kPa. Soil subsidence at pile S1's E side is less than its W side, and subsidence of soil mass at pile S2's S side is greater than its N side. Hence this negative/positive difference of soil subsidence between the two sides of each pile could induce corresponding variation of NSF along different sides of the piles.

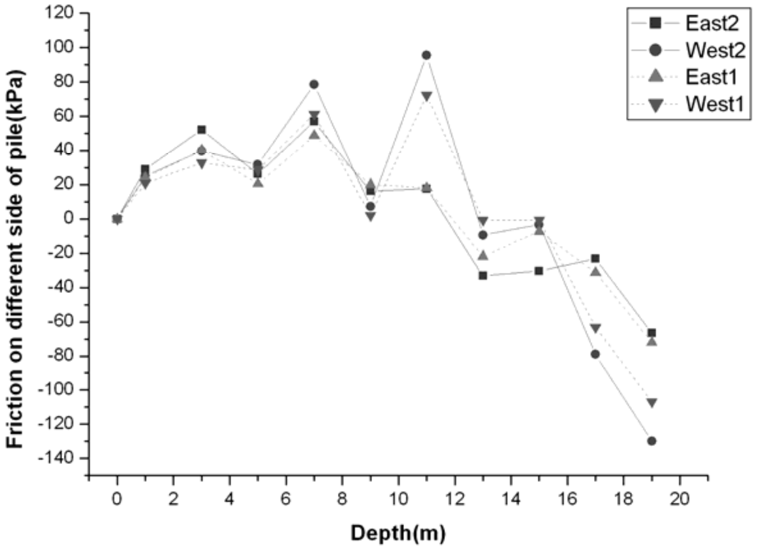


Fig. 6 Characteristics of friction on different side of piles due to nonuniform settlement of soil mass, in which East expresses the test pile, S2 while West is the test pile, S1; for S1 and S2, 1 and 2 note the E, W and N, S direction of stress gages in pile, respectively

4. CONCLUSIONS AND DISCUSSIONS

Here field testing data shows that seismic subsidence of loess ground indeed may generate a remarkable NFS along piles, which has been monitored by stress gages disposed in the piles with 2m interval. During this testing, average NSF and total NSF along pile in seismic subsiding loess field is about 54kPa and 1654kN respectively, which is much greater than NSF on pile in collapsing loess ground (Huang Xuefeng et al., 2002). Hence NFS induced by loess seismic subsidence should be accounted into design of piles foundation in those earthquake-prone loess areas.

The greater NSF along piles caused by seismic subsidence indicates a distinct difference of soil mass strength between non-saturated loess and saturated loess. In Fig. 6, the position of natural point is relative stable during the whole field testing, with a 13m depth along pile or a 15m buried depth. This depth of 15m is consistent with the above-mentioned bottom depth of seismic loess in the field. Relative stable position of natural point reveals that NSF's scope on interface between pile and soil, with the buried depth from 2m to 15m, is fixed and as a result only the one conclusion could be educed that with development of seismic subsidence there is no relative slide between pile surface and soil mass. Consequently, NSF along pile caused by seismic subsidence reported here is a kind of static friction (static NSF), whereas NSF related to typical loess subsidence by soaking should belong to a scope of kinetic friction (kinetic NSF). In our opinion, less seismic subsidence of loess field, e.g. observation points in the test site with an average subsidence of 22mm, is necessary for generating the static NSF.

Considering cost of stress gages and total channels of dynamic strain instrument, there are 20 gages symmetrically disposed into each pile, with a 2m interval, to observe NSF related to seismic subsidence induced by a short delay blasting. The interval of 2m is greater than 1m and this could restrict the estimating accuracy of NSF along piles. A short accuracy is likely able to slightly magnify the difference of NSF generated by seismic subsidence at different side of pile because there is not enough data to figure a delicate distribution of NSF and PSF along pile.

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