# Estimation of Peak Ground Acceleration From Canister Sliding Displacement Observed At North Anna Nuclear Power Plant During 2011 Virginia Earthquake

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**SUMMARY:**
Shaking from the Mw 5.8 Mineral, Virginia, earthquake caused sliding displacements of fuel canisters set on a concrete foundation stored at North Anna nuclear power plant, located 17 km from the epicentre. However, the unavailability of free-field accelerogram records at the North Anna site makes it difficult to model the sliding displacement analytically. Assuming that the canisters can be considered stiff and that they behaved like rigid bodies during the earthquake, a recently developed formulization enables us to predict sliding displacements using that induced by input sinusoidal ground acceleration. Applying the procedure inversely, we can estimate the peak ground acceleration (PGA) that caused the observed sliding displacements. The estimated PGA values are somewhat higher than the observed PGA value (0.27g) recorded by a strong motion instrument in the basement of a nearby containment facility. We explore alternative hypothesis to explain these results.

*Keywords: Sliding displacement, sinusoidal acceleration, peak ground acceleration, forensic analysis, canister*

## 1. INTRODUCTION

Shaking from the Mw 5.8 Mineral, Virginia, earthquake caused 4.5-inch (0.115-meter) sliding displacement of a fuel canister set on a concrete foundation stored at North Anna nuclear power plant, located 17 km from the epicenter. Of 27 canisters at the site, 25 were displaced by amounts ranging from 1” to 4.5”. However, since free-field accelerogram records at the North Anna site were unavailable, the severity of mainshock ground motions, at North Anna nuclear power plant, has thus remained unclear. An accelerogram in the basement of a nearby containment facility recorded a PGA of 0.27g on the NS component. In this report we present a preliminary quantitative analysis of the observed sliding displacements.

Conventionally, time history analysis, which can consider the complexity inherent in the phenomena of interest, of recorded accelerograms can be used to compute accurate sliding displacement of objects. However, the unavailability of free-field accelerogram records at the North Anna site makes it difficult to compute the sliding displacement and compare between the predicted sliding displacements with that observed.

To infer the sliding displacement for a given acceleration, one approach has been to employcharts available in the literature. Shao and Tung [1] prepared a chart of the mean-plus-standard deviation of the maximum sliding distance of an unanchored body. However, this study does not consider vertical excitation. Including effects of vertical excitation, Lopez Garcia and Soong [2] presented the fragility information for sliding-related failure modes. They classified the fragility curves according to the friction coefficient and peak horizontal ground acceleration. Historically, Newmark [3] presented a simple formula to determine the sliding distance of a freestanding body subjected to a single rectangular acceleration pulse at the base concerning earthquake response of embankments. Choi and Tung [4] concluded that Newmark’s formula could be used if an adjustment factor consisting of the friction coefficient and peak horizontal base acceleration was applied. However, the study is limited to the action of horizontal base excitation. As mentioned above, the previous procedures for estimating the slip displacement of the body do not consider the period of horizontal ground excitation, although Taniguchi [5] pointed out that the period of horizontal base excitation makes an important contribution to elongation of the slip displacement of the body in addition to the friction coefficient and peak horizontal acceleration. This suggests that estimating the sliding displacement from the charts may lead erroneous results. Taniguchi and Miwa [6, 7] developed a formulization to approximate the sliding displacement of a rigid body set on the ground including effects of peak ground acceleration, friction coefficient and predominant period of ground motion.

In contrast, applying the procedure developed by Taniguchi and Miwa [6, 7] inversely, Hough, et al. [8] inferred PGA from the scratch marks left on a ceramic tile floor by an industrial battery rack during Haiti earthquake. This paper uses the same strategy and tries to infer PGA at North Anna nuclear power plant from the sliding displacement observed by a canister.

## 2. BELIEF REVIEW OF TYPICAL DRY CASK STORAGE SYSTEM

At some nuclear reactors across the US, spent fuel is kept on site, above ground, in systems basically similar to the ones shown here (See Figure 1) [9]. Once the spent fuel has cooled, it is loaded into special canisters. Each canister is designed to hold approximately 2-6 dozen spent fuel assemblies, depending on the type of assembly. Water and air are removed. The canister is filled with inert gas, and sealed (welded or bolted shut). Some canisters are designed to be placed vertically in robust above-ground concrete or steel structures (See Figures 2 and 3) [10]. Each container is 16 feet tall and 8 feet in diameter. Therefore, the height/width aspect ratio is approximately 2:1. When fully loaded with 32 used nuclear fuel assemblies, each container weighs about 115 tons. [11]

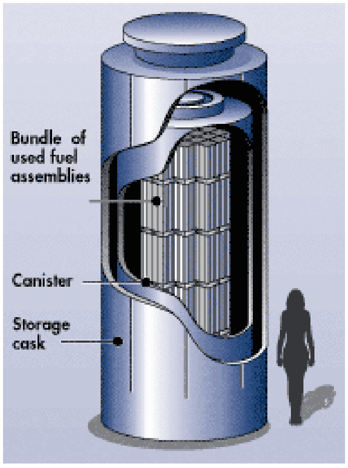


**Figure 1.** Typical dry cask storage [9]

**Figure 2.** Dry casks placed vertically in robust above-ground concrete at North Anna nuclear power plant site [10]

**Figure 3.** Dry casks placed vertically in robust above-ground concrete at North Anna nuclear power plant site (Close-up view) [10]

## 2. ESTIMATION OF PGA FROM SLIDING DISPLACEMENT

At the North Anna nuclear power plant shaking was strong enough to displace heavy canisters on the robust above-ground concrete shown in Figures 2 and 3. The canister was one of several rows of similar canisters in a large area on the robust above-ground concrete of the west side of the site. 25 of the 27 canisters have been moved from 1 inch to 4.5 by the earthquake, but they remained upright and stayed fully intact [12].

The scratch marks on the concrete told that the canister experienced sliding, but it did not tell exactly whether the canister experienced rocking. Judging from the relatively small displacement comparing to the dimensions of the canister, we assume that the canister experiences sliding but not rocking based on Taniguchi [5], who showed that an object experiences a relatively large sliding displacement if the sliding occurs during rocking due to deadweight reduction effects. The coefficient of friction during sliding is unknown, but we can estimate an upper bound given that the canister did not rock. We can then explore the range of PGA and predominant period of motion that will generate the observed displacements. As noted, observed displacements of 25 of 27 canisters were between 1” and 4.5” (.025-0.115 meter).

The coefficient of friction between the steel base plate of the canister and the robust above-ground concrete is a key parameter for our analysis, and is unknown. Established values for the coefficient of friction between steel and concrete are almost universally 0.3, except for a rough or fine finish of their surfaces. We therefore consider $\mu$= 0.3 to be a reasonable estimate, and use this value in our calculations. We note that this friction value, in combination with the aspect ratio of the canister, can explain why the canister did not experience rocking. In addition, Taniguchi [5] showed that an object could not rock on a low-grip foundation, since it cannot gain enough horizontal support force, which is necessary to initiate rocking.

To the extent that the canister behaves like a rigid body, its sliding displacement can be calculated even though its dimensions and its weight are unknown. Here, since water and air inside the canister are removed and filled with inert gas and the spent fuels and their retainers are assumed to be stiff, we conclude it is reasonable to assume the canister behaved like a rigid body in response to the earthquake. Taniguchi and Miwa [6, 7] presented the calculation for approximating the sliding displacement of rigid bodies during an earthquake based on a consideration of the sliding displacement induced by sinusoidal ground acceleration with the same maximum acceleration and predominant period as the earthquake of interest. Due to randomness of earthquake wave and discontinuous nature of sliding phenomena, an approximated sliding displacement naturally differs from an exact one and distributes probabilistically around the exact one. To infer a maximum sliding displacement from the approximated one, Taniguchi and Miwa [6, 7] presented correction factors based on probability of nonexceedance. Applying the procedure inversely, we are able to estimate the peak ground acceleration (PGA) that caused the observed 4.5-inch (0.115-meter) sliding displacement.

We use the results of Taniguchi and Miwa [7], who consider the slip displacement of a rigid body subjected to sinusoidal horizontal motions as an approximation for motion caused by earthquake shaking. (We will discuss the additional complication of vertical acceleration in a following section.) Taniguchi and Miwa [7] show that, in response to horizontal sinusoidal motion, the maximum relative displacement of a rigid body is given by:

$$x_{\sin} = \frac{1}{2}\mu g t_1^2 + \frac{A_{gx} g T^2}{4\pi^2}\sin\frac{2\pi}{T}t_1 + D_1 t_1 + D_2 \tag{2.1}$$

where $D_1 = -\mu g t_0 - \frac{A_{gx} g T}{2\pi}\cos\frac{2\pi}{T}t_0$, $\quad D_2 = \frac{1}{2}\mu g t_0^2 - \frac{A_{gx} g T^2}{4\pi^2}\sin\frac{2\pi}{T}t_0 + \frac{A_{gx} g T t_0}{2\pi}\cos\frac{2\pi}{T}t_0$

$$t_0 = \frac{T}{2\pi} Sin^{-1}\frac{\mu}{A_{gx}}$$

$$t_1 = \frac{T}{2\pi A_{gx}}\left(-\varphi + \sqrt{\varphi^2 + 2A_{gx}\left\{\phi + A_{gx}\left(1 - \frac{\pi^2}{2}\right)\right\}}\right) \tag{2.2}$$

where $\quad \varphi = \mu - \pi A_{gx}, \quad \phi = \mu\, Sin^{-1}\frac{\mu}{A_{gx}} + A_{gx}\cos\left(Sin^{-1}\frac{\mu}{A_{gx}}\right)$

where $A_{gx}g$ is the peak acceleration and $T$ is the period. We use equation (1) to calculation $x_{\sin}$ for $A_{gx}g$ = 0.1 – 1.5 g and $T$ = 0.1 – 1.5 s, assuming a $\mu$ value of 0.3.

A further consideration is that, as discussed by Taniguchi and Miwa [7], predicted slip from input sinusoidal motions, $x_{\sin}$ ,will differ from predicted slip from earthquake ground motions. On average, the mean ratio between exact displacement and $x_{\sin}$ is approximately 1. That is, 50% of earthquakes with a given $A_{gx}g$ are expected to produce a horizontal displacement greater than $x_{sin}$. Considering 104 earthquake records from sites around Japan, Taniguchi and Miwa [7] determine the probability density function (pdf) for a slip ratio, $\beta_{prob}$ for including the aspect of earthquake shaking complexity that elongates or shortens the displacement relative to that predicted for input sinusoidal acceleration:

$$x_{eq} = \beta_{prob} \; x_{sin} \tag{2.3}$$

Using the 104 recordings, Taniguchi and Miwa [7] derive values of $\beta_{prob}$ of 1.84 and 2.32 corresponding to probabilities of nonexceedance of 90% and 95%, respectively. That is, if we start with the observed displacement due to an earthquake, $x_{eq}$, the target displacement we seek to match using equation (1) is $x_{eq}/\beta_{prob}$, where we choose $\beta_{prob}$ for a desired probability of nonexceedance. Thus, to obtain a more statistically rigorous estimate of acceleration due to earthquake shaking, $A_{gxeq}g$, we should consider a target displacement of (0.025-0.115) m/1.84 to obtain an estimate of $A_{gxeq}$g with a 90% probability of nonexceedance, or (0.025-0.115) m/2.32 for a 95% probability of nonexceedance. In the following section we will use a target displacement of 1.36-6.25 cm to estimate $A_{gxeq}$g with a 90% probability of nonexceedance. The choice of a 90% probability of exceedance is arbitrary; we consider it a more reasonable, conservative estimate than an estimate corresponding to a 50% probability of exceedance, which has a significant chance of overestimating the true accelerations.

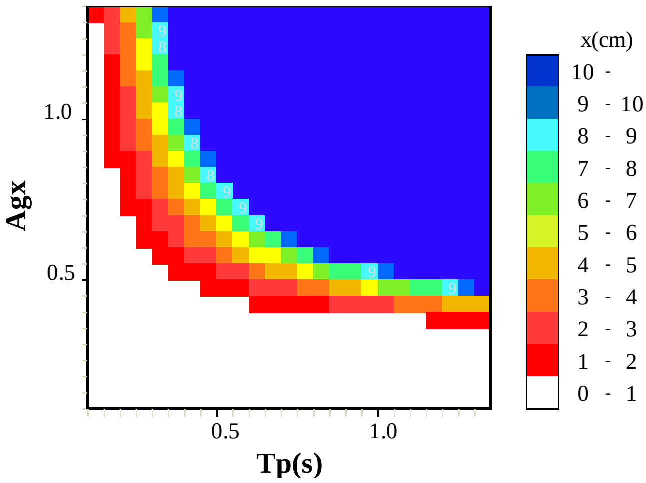


**Figure 4.** Predicted displacement in cm (color scale indicated) as a function of predominant period of shaking, $T_p$, and peak acceleration, $A_{gx}g$, for a $\mu$ value of 0.3. Red swath indicates values that predict maximum displacement values of 1-2 cm , the target displacement to estimate $A_{gxeq}g$ with a 90% probability of nonexceedance.

The range of $A_{gx}/T_p$ values that predict displacements of 1.36-6.25 cm are found to be upwards of 0.35g for reasonable values of $T_p$. ($T_p$ is the dominant period of ground acceleration). $A_{gx}g$ is upwards of 0.4$g$ for $T_p$=0.5s, a value that is reasonable in light of the recorded ground motions at the nearby containment facility.

According to Shakemap us082311a [13] disseminated by U.S. Geological Survey, the recorded PGA at a station #23117 near the North Anna nuclear power plant site was about 20%g. A strong motion instrument in the basement of a containment facility at the site recorded a PGA of 27%, with the strongest motions on the north-south component. Our preliminary estimates of peak shaking are thus somewhat higher than the recorded value. Moreover, from first principles one predicts that the casks will not move unless shaking exceeds 30%g given a coefficient of friction of 0.3. We can suggest several alternative hypotheses to explain this apparent discrepancy: 1) the coefficient of friction differs significantly from the standard value for steel versus concrete due to special design used for the casks and/or the concrete pad; 2) free-field accelerations were somewhat larger than those recorded within the nearby structure; 3) the casks did not respond as rigid bodies, but rather with displacements that reflected the internal response of the component; 4) the response of the casks was significantly influenced by vertical ground motions, as discussed below.

The vertical component of slip can effectively reduce or increase the acceleration of gravity. As noted by Taniguchi and Miwa [7], the effects of varying vertical acceleration on the body will have minimal contribution to the displacement given the short time a body is in motion. To provide an adequate safety margin for predictions of displacement for a given ground motion, Taniguchi and Miwa [7] assume a monotonous reduction in friction due to vertical acceleration. Considering 144 accelerograms with peak horizontal accelerations scaled to 9 $m/s^2$, they calculate that introducing a monotonous reduction in friction increases the displacement on average by 19%. For a body on a ground floor, the nominal coefficient of friction, $\mu'$, is given by

$$\mu' = \mu(1 - PVGA \cdot \sigma/g) \tag{2.4}$$

where PVGA is the peak vertical ground acceleration and $\sigma$ is the standard deviation of the ratio of the vertical ground acceleration to the peak vertical ground acceleration at the instant of the peak horizontal shaking.

In this study we are not seeking to predict displacement for a given ground motion but rather to infer ground motion for a given displacement. The effects of varying vertical acceleration, which could either increase or decrease effective friction, are unknowable but will introduce an additional factor of uncertainty.

To explore the possible effect of vertical accelerations we assume $\sigma$ = 0.46 and vertical acceleration, PGVA, to be 0.5 horizontal PGA, following Taniguchi and Miwa [7]. Assuming horizontal PGA of 0.25g and that vertical acceleration monotonically lowers $\mu'$, equation (4) yields $\mu'$=0.94$\mu$. If we lower our estimates of $\mu$ from 0.3 accordingly (i.e., to 0.29), the range of inferred $A_{gx}$ values is lowered only slightly. As discussed by Taniguchi and Miwa [7], the target displacement also changes if one considers the effects of vertical base acceleration. For 90% probability of exceedance, the target displacement is 6.8 cm (i.e., (11.5 cm)/1.69). It is possible, however, that the effects of vertical acceleration were less negligible for one individual case than they are expected to be in general. If the vertical ground motions were such that $\mu$ was lowered by more than a typical amount, this would have generated larger displacements than predicted using our approach.

Here, we return to the case that the casks did not respond as rigid bodies, but rather with displacements that reflected the internal response of the component. If the internal response is expected, equations (1) to (4) no longer stand. However, applying a few assumptions, we can continue to explore the PGA further. Although the natural frequency of the internal component is unknown, an amplification ratio of the response of the internal component to the ground motion is naturally expected to be upwards of two or three. The response of internal component makes the canister slide further, because the response works as nominal force to push the canister further. In a sense, it seems that the response cancels out the friction effect. We roughly estimate its effects by reducing the friction coefficient. If the internal component responds as much as two times to the ground excitation, the nominal friction effect is reduced in a half of its original value. Similarly, if the internal component responds as much as three times to the ground excitation, the nominal friction effect is reduced in a third of its original value.

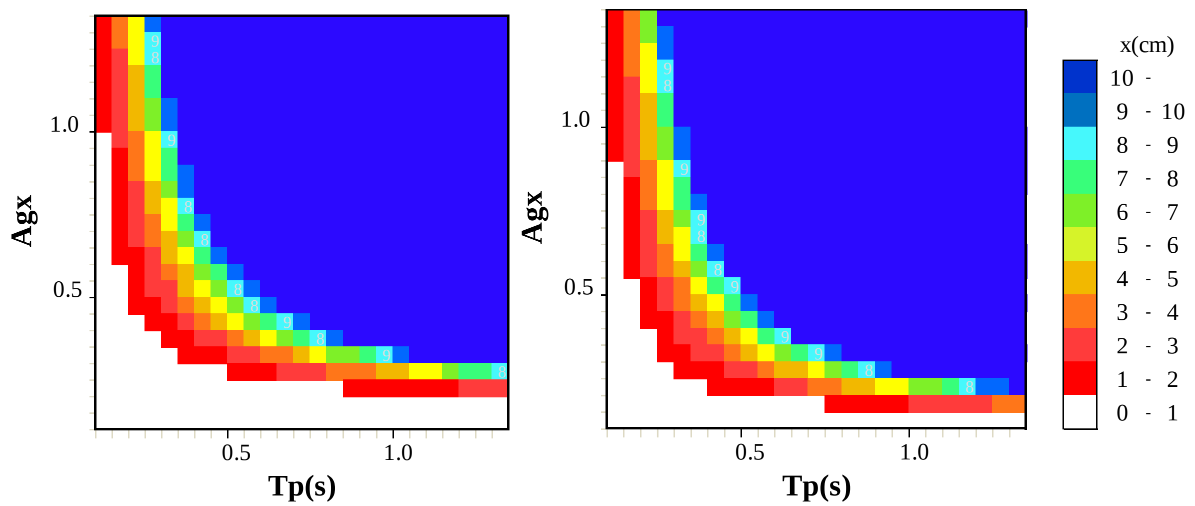


**Figure 5.** Predicted displacement in cm (color scale indicated) as a function of predominant period of shaking, $T_p$, and peak acceleration, $A_{gx}g$, for $\mu$ values of 0.15 (right) and 0.1 (left). A $\mu$ value of 0.15 corresponds that the internal component responds as much as two times to the ground excitation, while a $\mu$ value of 0.1 corresponds that of three times. Red swath indicates values that predict maximum displacement values of 1-2 cm, the target displacement to estimate $A_{gxeq}g$ with a 90% probability of nonexceedance.

The range of $A_{gx}/T_p$ values that predict displacements of 1.36-6.25 cm are found to be upwards of 0.15g for reasonable values of $T_p$. $A_{gx}g$ is upwards of 0.2$g$ for $T_p$=0.5s in a $\mu$ value of 0.15, while that for $T_p$=0.3s in a $\mu$ value of 0.1. These PGA values are very close to the recorded PGA at a station #23117 near the North Anna nuclear power plant site. In addition, the results suggest that the response of the internal component of the canister is a possible mechanism to induce the sliding displacement.

## 3. CONCLUSION

We have presented a detailed forensic analysis of a cases of documented rigid body displacement to obtain quantitative estimates the severity of ground motions North Anna nuclear power plant during the 23 August 2011 Virginia earthquake. From detailed analysis of the displacement of the canister observed at North Anna nuclear power plant we estimate a range of mainshock PGA values of approximately 0.35-0.5$g$. Because this level of shaking corresponds to a 90% probability of nonexceedence, this estimate is considered conservative. This estimate is relatively imprecise, but it is somewhat higher than the recorded PGA at a station #23117 near North Anna nuclear power plant site. In contrast, if the response of the internal component of the canister is expected, the PGA required to displace the canister is very close to the recorded PGA at the station #23117. However, we have discussed several explanations for the apparent discrepancy: in future work we will explore these further.

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