A Comparative Study on Effectiveness of Using Horasan Mortar as a Pure Friction Sliding Interface Material

A.A. Kasimzade, A. Dushummana, S. Tuhta, G. Atmaca, F. Günday, K. Pfidze, and O. Abrar

Abstract—In this study, the possibility to use Horasan mortar as a sliding interface material for pure friction aseismic isolation system is investigated. Both experimental and numerical studies are conducted to examine the effectiveness of using this material in structural isolation systems of buildings with no overturning moment, as it has shown some attractive experiences in time based on the existing related literature. Responses of four storey lightweight building are numerically investigated by finite element modelling in MATLAB; whereas the University Consortium on Instructional Shake Table (UCIST) is used to study the responses of the same building during experimental works. Comparison of both studies is shown to be in a good agreement in terms of resulting structural response accelerations, velocity and displacements. Approximately 28 - 31 % reduction of base floor acceleration is achieved; and the maximum sliding velocity and displacement are found to lie between 0.33–0.45 m/sec and 0.0353–0.0559 m respectively; which fall within the recommended standards' limits. As a result, these findings demonstrate the effectiveness of using Horasan mortar as friction interface material which has additionally gained experience in more than ten centuries.

Keywords—Horasan mortar, Long-time performance, pure friction seismic isolation system, UCIST

I. INTRODUCTION

Pure friction seismic isolation systems mainly depend on the friction coefficient. In other words, without friction, the building would return to its initial position as soon as the earthquake duration time ends [1]. However, the existence of friction makes the building stays away from its original position after earthquake. This type of system allows the building to possess no single natural period, thus leading to a non-resonant motion behavior. A number of researches have been conducted on this type of sliding material and its characteristics were experimentally studied [2-4]. The Natural Seismic Isolation (NSI) with Horasan mortar as the interface material was devised when the “Walled Obelisk” monument was modeled for investigation in terms of its structural safety [1, 5-11]. The results of the research showed that the bottom part of the monument acts as a frictional responsive seismic isolator. It was shown that the bottom part of the monument acts as the NSI device with three steps and four sliding interfaces. The coefficients of friction were found to be 0.25 for graphite powder, 0.34 for dry sand, and 0.41 for wet sand [12, 13]. For masonry buildings, coefficients of friction have been reported as 0.2 for derlin, 0.6 for asphalt, and 0.7 for vinyl florin [14].

Several bricks with and without sliding joint have also been tested under lateral loads with simulated dead load [15]. The other tests on shake table have demonstrated that the friction coefficients are 0.23 for graphite/concrete interface at a peak acceleration of 0.2–0.3 g; and 0.4 for the same interface at a higher peak acceleration of (0.3–0.6) g. Dune sand, clay and lightweight expanded clay having coefficients of frictions of 0.25, 0.16 and 0.2-0.3 respectively were used as pure friction systems for an adobe building in Iran and the results showed that dune sand and lightweight expanded clay can be good materials to create sliding layers[16].

In the study of Nishimura et al [17, 18], the experimental damping coefficient, static frictional coefficient, dynamic frictional coefficient and frictional coefficients were assigned as c = 0.03 - 0.352, \( \mu_{\text{max}} = 0.17 - 0.22, \mu_{\text{min}} = 0.07 - 0.09, \mu = 0.05 - 0.1 \) respectively. It was also shown that even if \( \mu = 0.1 - 0.2 \), it could be effective in the case of strong earthquakes. In the same study, two different types of stainless steel were proposed as sliding bearings and both the accelerations and inter-storey drifts were reported to be reduced by 20–40%. The static and dynamic frictional coefficients were assigned to 0.2 and both the accelerations and inter-storey drifts were reduced by 40–80% in the case of 4-11-degrees of freedom, which shows that the response reduction effect was more than expected under a significantly larger earthquake even when the friction coefficient was \( \mu = 0.2 \).

Shake table tests were conducted on the same materials and the optimum friction coefficient were found to be 0.1 and 0.2, respectively. Furthermore, Nishimura et al. [19] conducted another research on the results of two previous studies, where they investigated a metal-touched type base isolator, for which they assigned the experimental damping coefficient, static frictional coefficient and dynamic frictional coefficient as \( c = 0.096 - 0.153, \mu_{\text{max}} = 0.17 - 0.21, \) and \( \mu_{\text{min}} = 0.11 - 0.16 \) respectively, and used a simulation to evaluate the response reduction effect of a multi-degree-freedom system model. The responses were in the range of 50–80% reduction. The responses of interest for PF systems including friction coefficient, peak sliding velocity and displacement, are shown for various other researchers [5-11, 20-24]. In this study, authors aim to demonstrate the possibility to use Horasan mortar as a

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A.A. Kasimzade is a Professor at Ondokuz Mayis University, Civil Engineering Department, Samsun, Turkey (e-mail: azer@omu.edu.tr).

A. Dushummana is with Ondokuz Mayis University, Civil Engineering Department, Samsun, Turkey (e-mail: alyoudushumman@yahoo.fr).

S. Tuhta is with Ondokuz Mayis University, Civil Engineering Department, Samsun, Turkey (e-mail: stuhta@omu.edu.tr).

G. Atmaca is with Provincial Directorates of Disaster and Emergency, Samsun, Turkey (e-mail: gencayatmaca@hotmail.com).

F. Günday is with Ondokuz Mayis University, Civil Engineering Department, Samsun, Turkey (e-mail: furkan.gunday@omu.edu.tr).

O. Abrar is with Ondokuz Mayis University, Civil Engineering Department, Samsun, Turkey (e-mail: obaidullah.abrar@gmail.com)

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sliding interface material in pure friction seismic isolation systems of structures with no overturning moments.

II. GOVERNING EQUATIONS FOR P-F ISOLATION SYSTEMS

A. Frictional Model for the Pure Friction (P-F) Seismic Isolation System

Considering velocity dependency, the frictional coefficient is expressed as shown in Eq. 2.1. [25, 26].

\[
\mu (v) = \mu_{\text{min}} + (\mu_{\text{max}} - \mu_{\text{min}})e^{-d|v|}
\]  
(2.1)

Where d is the parameter for velocity dependency; v is the sliding velocity; \(\mu_{\text{min}}, \mu_{\text{max}}\) are the minimum and maximum friction coefficients respectively [27,28]. Based on the relation presented by Eqs. 2.2–2.4,

\[
F_\mu = \mu N = \mu Mg
\]  
(2.2)

\[
M = m_0 + m_{ss}
\]  
(2.3)

\[
m_{ss} = \sum_{i=1}^{n} m_i
\]  
(2.4)

The sliding phase can be defined by relation (Eq. 2.5)

\[
\frac{m_0}{m} (\ddot{u}_s - \ddot{u}_b) + \frac{c_1 u_1 + k_1 u_1}{m} \geq \mu g
\]  
(2.5)

Equation of motion can be exhibited by a set of system of differential equations as (Eqs. 2.6a and 2.6b).

\[
m_0 \ddot{u}_0 + \mu Mg \text{ sgn} (\dot{u}_0) - c_1 \dot{u}_1 - k_1 u_1 = m_0 \ddot{u}_g
\]  
(2.6a)

\[
[m] \{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = \frac{\mu Mg}{m_0} \text{ sgn}(\dot{u}_0) - \frac{c_1 u_1 + k_1 u_1}{m_0} \{1\}
\]  
(2.6b)

Otherwise, if the condition (Eq. 2.5) is not met, equation of motion becomes as (Eq. 2.7),

\[
[m] \{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = + \ddot{u}_g [m] \{1\}
\]  
(2.7)

Where \text{ sgn} is defined as (Eq. 2.8).

\[
\text{ sgn} = \frac{1}{\mu g} \left[ \frac{m_0 (\ddot{u}_g - \ddot{u}_0) + c_1 u_1 + k_1 u_1}{M} \right], \text{ if } |\ddot{u}_0| = 0
\]  
(2.8)

\[
\text{ else if } \ddot{u}_0 > 0, \text{ sgn} = 1,
\]

\[
\text{ else } \text{ sgn} = -1
\]

Parameters included in Eq. 2.2–2.8 are illustrated and explained in Fig. 2.1. Here [m], [c], [k] are mass, damping, and stiffness matrices respectively, u is displacement, \(\dot{u}_0\) is velocity, \(\ddot{u}_0\) is base displacement, \(\ddot{u}_g\) is earthquake acceleration. The set of high non-linear equations (2.5–2.8) are solved in MATLAB environment by using finite element modelling and the Runge-Kutta 4th order algorithm. Referring to Kasimzade et al. [1], Horasan mortar parameters shown in Eq. 2.1, are obtained as

\[
\mu_{\text{max}} = 0.37, \quad \mu_{\text{min}} = 0.26, \quad d = 11
\]  
(2.9)

Fig. 2.1 Illustration of the n story building’s mathematical model with frictional bearing

III. NUMERICAL CASE STUDY

Horasan mortar as a P-F sliding interface material is applied for a four-storey hospital building with Hollow brick filled asmolene flooring (HBFaf), for which mass [m], damping [c] and stiffness [k] matrices were constructed by finite element method [29] as presented in (Eqs. 3.1–3.3).

\[
m_0 = 0.92192125 \times 10^6
\]  
(3.1)

\[
[k] = 1.0 \times 10^{10} \begin{bmatrix}
1.3427 & 0 & 0 & 0 \\
0 & 1.3323 & 0 & 0 \\
0 & 0 & 1.3323 & 0 \\
0 & 0 & 0 & 1.0887 \\
\end{bmatrix} \text{ (kg)}
\]  
(3.2)

\[
[c] = 1.0 \times 10^{7} \begin{bmatrix}
3.7440 & -2.1600 & 0 & 0 \\
-2.1600 & 4.3200 & -2.1600 & 0 \\
0 & -2.1600 & 4.3200 & -2.1600 \\
0 & 0 & -2.1600 & 2.1600 \\
\end{bmatrix} \text{ (N/m)}
\]  
(3.3)

\[
[m] = 1.0 \times 10^{9} \begin{bmatrix}
2.1238 & -0.6996 & -0.1364 & -0.0603 \\
-0.6996 & 2.1669 & -0.7353 & -0.1664 \\
-0.1364 & -0.7353 & 2.0967 & -0.8045 \\
-0.0603 & -0.1664 & -0.8045 & 1.3405 \\
\end{bmatrix} \text{ (Nm/s)}
\]  
(3.4)

Table I. Summary results from Numerical study by Finite element modeling in MATLAB

| NM&R | \(\ddot{u}_g\) | \(\ddot{u}_b\) | PR | \(u_b\) | \(u_g\) | Res. |
|------|----------|----------|----|--------|--------|------|
| FEMM | 8.05     | 5.7955   | 28.0154 | 0.0353 | 0.0353 |

NM&R: Numerical Method and Results; FEMM: Finite Element Modeling in MATLAB; PR: Percentage Reduction; Res.: residual displacement; \(\ddot{u}_g\): input acceleration (m/sec^2); \(\ddot{u}_b\): base floor acceleration (m/sec^2); \(u_g\): base floor displacement (m)
As seen from Table I and Fig. 3.1-3.4 the structure base acceleration is decreased by approximately 28.0154%; for Horasan mortar interface in comparison with input earthquake acceleration. Furthermore, it is clearly shown that the maximum base sliding velocity and displacement are 0.4511 m/sec and 0.0353 m respectively.

IV. EXPERIMENTAL CASE STUDY

The four storey hospital building [1] idealized as a rigid concrete mass and scaled to fit UCIST shake table (Fig. 4.4e), and its dimensions shown in Table I, were derived based on dynamics of similitude laws which are also adopted by other researchers [30-36].

Table I. Dimensions of the concrete model mass

| Mass (Kg) | X(m) | Y(m) | Z(m) | Volume(m³) |
|-----------|------|------|------|------------|
| 6.29      | 0.18 | 0.18 | 0.08 | 0.002592   |

A. Horasan Mortar Properties

Horasan mortar which is used as frictional interface material is composed of components shown in Table II [37].

Table II. Mixing of Horasan mortar components

| Component Name     | Sample components’ weight for 1kg |
|--------------------|-----------------------------------|
| Fractured bricks (g)| 426.5                             |
| Tras (Puzzolan) (g) | 111.1                             |
| Streamed sand (g)  | 258.2                             |
| Hydraulic lime (g) | 56.1                              |
| Water (g)          | 140-161.9                         |
| Total (g)          | 991.9                             |

The time scaling factor adopted in this study was derived based on equation which is also demonstrated by other authors [34, 35].

\[
\frac{T_{org}}{T_{sc}} = \sqrt{S} \tag{4.1}
\]

Where, \( T_{org} \) is the original earthquake time duration, \( T_{sc} \) is the scaled time duration. In this study, the time scale factor which is found as 6.4 is multiplied by resulting displacements to fit with UCIST recommendations. Accelerations are left unchanged based on the requirements of dynamic similitude laws [30-36].

\[
\frac{a_M}{a_P} = 1 \tag{4.2}
\]

Where; \( a_M \) is the acceleration of the model and \( a_P \) the acceleration of prototype.

UCIST shake table tests’ summary is shown in Fig. 4.4 below:
Fig. 4.4 Shake table test: Components, installation and (Computer equipped with Wincon before excitation (a); shake table with concrete model mass equipped with accelerometer (b); Horasan mortar collapse after earthquake and residual displacement measurement (d); Real time responses (e); installation of sample on top of shake table (c); and the whole system for shake table (f).

Table III. Summary of the 20 model averaged results from experimental study by UCIST Shake table

| EM&R | $u_g$ | $u_p$ | PR  | $u_b$ | Res. |
|------|------|------|-----|-------|------|
| FEMM | 8.08 | 5.65 | 30.85 | 0.0559 | 0.0493 |

As seen from Table III and Fig. 4.4 the structure base acceleration was decreased by approximately 30.85%; for Horasan mortar interface in comparison with input earthquake acceleration. Furthermore, it is clearly shown that the maximum base sliding velocity and displacement are 0.325 m/sec and 0.0557 m respectively.

V. COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

In this study, the comparison of numerical studies from FEMM method and the experimental studies from UCIST was done in order to examine the effectiveness of using Horasan mortar as a sliding interface material in pure friction aseismic isolation system of buildings with no overturning moment. Responses of interests are summarized in Table I.
According to the obtained results in Table I, it is clear that the used input earthquakes are nearly similar. The obtained peak sliding displacements from FEMM are quite less than the ones obtained from experiment. This slight difference might be interpreted as either coming from discrepancies and errors in measurements during test or from numerical studies. Additionally, velocity dependent friction parameters (Eq. 2.1) of Horasan mortar were assumed to be similar to ones calculated in [1, 37], but in reality they should be defined by in-situ shake table tests. The obtained peak velocities lie within 0.325-0.4511 m/sec, which is a safe interval compared to the maximum allowable velocity (0.7 m/sec) [11]. The obtained peak sliding displacements also lie well within the maximum plinth projection limit (i.e. 75 mm) [23, 24]. An excellent agreement is found for base floor accelerations from both experimental and numerical studies with only a slight difference of 2.51%.

VI. CONCLUSION

In this study, the performance of Horasan mortar as a pure friction sliding interface material was investigated. Experimental and numerical studies were compared and the findings are summarized as shown below:

- Experimental and numerical studies were shown to be generally in a good agreement with only slight differences which might have been caused by discrepancies and errors resulting from use of UCIST, as well as deriving model from prototype structure. Additionally, in reality Horasan mortar frictional parameters presented in Eq. 2.1 should be defined by in-situ shake table tests;
- The Natural Seismic Isolation (NSI) system made by Horasan mortar was able to reduce the input earthquake significantly, where the base floor acceleration reduction for both studies was approximately between 28 - 31% compared to input acceleration.
- Residual displacements from both studies are also found to have a good agreement with negligible differences.
- The peak sliding displacements found for numerical and experimental studies fall within the safe range compared to the recommended plinth projection limit which is 75mm as shown by Nanda et al [23, 24].
- The maximum velocity found experimental and numerically were much lower than the velocity limit (0.7 m/sec) which can damage sensitive equipment involved inside the building, thus showing the ability of Horasan mortar to keep structure move with acceptable speeds.
- Based on the findings shown above, it is therefore clear that Horasan mortar can be used as a sliding interface material for buildings with no overturning moments, because this material has gained experience in time and demonstrated the ability to keep its characteristics for long-term period.

### Table I. Comparison of the responses of interests from the experimental and numerical study

| Modelling method and software | Finite Element Modelling by MATLAB (FEMM) | Scaled Experimental Study with UCIST | Derivatives of \( a_b \) by Seismo soft | Comparison difference (%) for UCIST and FEMM |
|-------------------------------|------------------------------------------|------------------------------------|----------------------------------------|---------------------------------------------|
| Excitation earthquake         | Duze                                     | Scaled Duze                        | -                                      |                                             |
| Type of Filling of asmolene Flooring | SBFaf                                   | Scaled SFaf                         | -                                      |                                             |

Responses of Structure

| \( \ddot{u}_b (m/sec^2) \) | 8.0511 | 8.08 | 8.08 | -0.359 |
|--------------------------|--------|------|------|--------|
| \( u_b (m) \)           |        |      |      |        |
| Extremum                 | 0.0353 | -    | 0.0559 | -58.35 |
| Residual                 | 0.0353 | 0.0459 | 0.0459 | -30.02 |
| \( V_b (m/sec) \)       |        |      |      |        |
| Extremum                 | 0.4511 | 0.325 | 0.325 | 27.95  |
| Residual                 | 0.1077 | 0.021 | 0.021 | 80.50  |
| \( a_b (m/sec^2) \)     |        |      |      |        |
| Extremum                 | 5.7955 | 5.65 | 5.65 | -2.51  |
| Residual                 | 0 | 0 | 0 | 0 |
| \( a_b \) Reduction (%) | 28.0154 | 30.85 | 30.85 | - |

HBFaf: Hollow Brick Filled Asmolene Flooring

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