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STRUCTURAL HEALTH MONITORING AND IMPLEMENTATION OF RAPID RESPONSE PLANNING FOR UAE BUILDINGS

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ABSTRACT: Occupants in essential facilities such as hospitals, emergency operations centers, strategic military installations, critical financial institutions/centers, nuclear power plants, and ultra-tall buildings, cannot easily evacuate immediately after an earthquake or wait for a detailed safety assessment to reoccupy and resume operations. The decisions to evacuate and reoccupy are difficult, especially under a state of emergency, and can have dire consequences (stampede related injuries, significant loss due to unnecessary downtime, etc.). Consequently, several UAE buildings were selected for Structural Health Monitoring (SHM) and implementation of Enhanced Rapid Post-Event Assessment program aimed to avoid unnecessary evacuation and shutdown and/or minimize downtime. Nine high-profile buildings across Abu Dhabi and Dubai have been instrumented. The real-time structural monitoring systems provide intuitive onsite display, alerting, and remote notification on exceedance of demand/design parameters such as interstory-drift, absolute acceleration, and response spectra. This information, which is continuously, immediately and remotely available to building personnel, is useful throughout all phases of the post-earthquake response, inspection, and recovery process. Engineering services included comprehensive performance-based earthquake engineering risk analyses and (for some) implementation of custom ATC-20 style onsite rapid post event assessment planning. Presented here is an overview of the enhanced rapid post-event assessment solution along with case studies.

1. Introduction

Occupants in essential facilities such as hospitals, emergency operations centers, strategic military installations, critical financial institutions, and nuclear power plants, cannot easily evacuate immediately after an earthquake or wait for a detailed safety assessment to reoccupy the facility and resume operations. Hospitals and medical facilities, in particular, have a profound need to maintain building operational status and function in the aftermath of strong earthquakes to allow continued care for current patients and also to receive new patients injured by the disaster (Celebi et.al. 2004), (Wilson et.al. 2004). Also, critical financial institutions cannot afford unnecessary evacuations following and earthquake as these eventually turn into losses due to downtime and business disruption.

In earthquake-prone areas the inspections performed by municipalities and mutual aid volunteer inspectors, usually 3-10 days after the earthquake, are rapid safety assessments. But a more detailed structural evaluation is often recommended to determine building condition at the owner's expense (Building Occupancy Resumption Program 2001).

In order to avoid these unnecessary evacuations and minimize expensive downtime, a proactive system solution to performing rapid, detailed, and accurate post-earthquake safety assessment of these facilities is needed.

Post-event assessment (PEA) refers to the inspection and safety evaluation of a structure following a significant event such as an earthquake. PEA standards and response programs not only benefit building owners and municipality officials, they help to create innovative and proactive solutions for performing rapid and accurate evaluations.

San Francisco and several other forward-thinking jurisdictions have established Building Occupancy Resumption Programs (BORP) that permit the building's "engineer-on-call" to be pre-deputized to perform ATC-20 Green/Yellow/Red building tagging in lieu of official inspectors (Building Occupancy Resumption Program 2001), (Applied Technology Council 1989). This has lead to engineering companies offering rapid post-event assessment (RPEA) services. The US Navy independently developed a similar innovative Rapid Evaluation and Assessment Program (REAP) for their west coast hospitals and medical facilities (Swanson et.al. 2011). The common goal among these rapid PEA programs is to formalize and pre-organize the PEA response and process.

A key aspect in RPEA process is the onsite safety inspection. Traditional visual-based inspections can impose high costs and inconvenience on building owners and occupants alike. For example, physical access to structural members usually requires the removal of non-structural components such as interior partitions and fireproofing. The post-earthquake detailed inspection requirements of welded steel moment frame buildings with pre-Northridge Earthquake style connections can be especially time consuming and costly to implement (Federal Emergency Management Agency 2000). Prolonging expensive downtime, limited resources such as qualified inspectors may not be immediately available after a damaging event, especially for dense urban areas. Enhanced RPEA refers to the services previously described but enhanced by utilizing timely information afforded by advanced structural monitoring systems.

Several buildings in the United Arab Emirates have been equipped with permanent structural health monitoring systems as part of an enhanced rapid post-event assessment service. The primary goal of these systems is to provide useful information throughout the RPEA process and implementing a response plan accordingly.

An overview of this network of buildings, the structural health monitoring system and its integration within the rapid PEA response process is provided in the following sections. Several case studies are then presented.

2. SHM Systems in the United Arab Emirates

2.1. The Abu Dhabi SHM Network

To assure sustainable development of the Emirate of Abu Dhabi, and cultivate a disaster-free living environment for its citizens, the Abu Dhabi Municipality initiated the project "Assessment of Seismic Hazard and Risk in Emirate of Abu Dhabi (Milutinovic et.al. 2013). The primary objective was to develop a state-of-the-art system to assess, monitor, mitigate, and update the seismic hazard and risk that exists in the Emirate. As part of this large innovative project, one task included the design and implementation of a structural health monitoring network of seven unique and tall buildings distributed throughout the Emirate. Some participating buildings are shown in Fig 1.

2.2. SHM Systems in Dubai

The Survey Department of the Dubai Municipality, as part of its ongoing activities to provide real-time monitoring of seismic activity in the region and create public awareness, chose two important buildings to implement SHM systems including response planning. The primary objectives are preventing unwarranted distress among Dubai citizens, reducing business interruption caused by unnecessary evacuations, and minimizing periods of downtime waiting for official decision to reoccupy (Dubai Municipality Survey Department 2014). These buildings are the Shaikh Rashid Tower at the Dubai World Trade Centre (DWTC) and the Burj Khalifa, shown in Fig 2.

Fig. 1 – Abu Dhabi SHM Network.

Fig. 2 – SHM Systems in Dubai.

3. Structural Health Monitoring System Overview

The structural health monitoring system described here is OASIS (On-line Alerting of Structural Integrity and Safety) system from Kinemetrics, Inc., Fig. 3. The OASIS system is a flexible structural monitoring system that provides for the collection and processing of real-time acceleration, velocity, displacement, and inter-story drift data. The OASIS monitoring system consists of three major hardware subsystems; sensors, data acquisition, and the display and alarm system.

Accelerometers are the sensor of choice due to their robustness and ease of installation. For buildings, interstory drift is the critical response quantity of interest, but since no sensor currently exists that can reliably capture relative story displacements (Skolnik et.al. 2010), double numerical integration is performed on the real-time acceleration data. This difficult method requires several signal processes such as linear band-pass filtering and is one of the primary functions of the OASIS software.

The central recording unit provides the necessary tools for continuous real-time and event-driven data acquisition such as precise GPS-based timing, power supply and management, signal processing, analog-to-digital conversion, and data file formatting and storage. It also provides the necessary communication interfaces for the PC display and alarm system. Central data recorders, compared to distributed or wireless networks, remain the only commercially viable solution for such demanding applications requiring robust permanent systems. Although running long analog sensor cables can be expensive, wireless technology, while promising, is not yet mature enough. Wireless-power for example is still in technological infancy and probably will be for some time. Thus, replacing analog cabling with wireless technology (or distributed recorders) requires local power supply at each sensor (or recorder) location which in-turn increases upfront costs in both hardware and implementation as well as in maintenance demand. This is especially true considering that sensors are typically located in difficult areas to access such as above ceiling tiles. Another challenge with wireless technology stems from the limited data buffering capacity at the sensor node preventing packet re-transmission leading to permanent gaps data, which may negatively impact overall results and real-time processes.

Fig. 3 – OASIS structural health monitoring system.

The display and alarm cabinet consists of a rack-mounted industrial computer with alarm panel, router/firewall, and UPS backup power. OASIS software running on the computer is responsible for controlling the alarm panel, performing real-time processes (e.g., double numerical integration), and providing interactive display for user control. A host of notification methods (i.e., email, FTP, SMS, etc.) are available per user discretion.

4. Rapid Post-Event Assessment Process

A key aspect in the successful enhancement of a rapid PEA process is the integration of the monitoring system within the overall process.

The onsite response action immediately after the shaking and the "dust settles" is crucial. The natural inclination of most occupants is to immediately evacuate a building following a major earthquake. Avoiding unnecessary evacuations is critical especially for essential facilities such as hospitals; acute care medical facilities, emergency operations centers, strategic military installations, nuclear power plants, and prisons and detention centers. Occupants of these facilities cannot easily evacuate immediately after an earthquake and wait for a detailed safety assessment to reoccupy the facility and resume operations. Therefore, the goal with respect to immediate response is more about enabling continued occupancy and operation, and less about triggering an evacuation as is often thought to be the case. The OASIS system alarms and notifications provide confidence to building operation personnel that it is OK to recommend occupants stay inside and continue "business as-usual" or commence emergency response/cleanup operations. It is also important to note that onsite building operation personnel may trigger an evacuation for reasons other than structural damage. Damage to contents or building systems may prevent continued operation of the facility, and so onsite personnel require occupancy evaluation guidance that is broader than just the structural response information from the monitoring systems.

The post-earthquake inspection occurs as soon as possible but can be up to a few days to weeks depending on the extent of regional damage and the contractual arrangement between the facility and inspecting engineers. Event information from the OASIS system can be used to aid inspecting engineers in the inspection and tagging process. For example, specific floors that exceeded thresholds can be initially targeted for inspection. More detailed building response data may be provided using post-processing tools and the results presented in a brief report or handout to supplement the immediate information provided by the OASIS system. This quantitative information is an invaluable supplement to the usual post-earthquake inspection process, which is based predominately on visual indicators of damage. This is especially the case in modern buildings with cladding and interior systems that prevent access to the underlying structure. In these cases the level of structural damage must be inferred from damage to non-structural systems, which is dependent on particulars such as the quality of detailing, etc., and therefore highly variable. The quantitative data provided by the monitoring system helps inspecting engineers reach less conservative conclusions regarding the acceptability of the subject building for continued occupancy.

Lastly, the detailed evaluation and recovery can extend over a period of months. Main event and the inevitable aftershock data can aid in the subsequent engineering evaluation in assessing potential damage, need and priority of any structural system inspections, and extent of required repairs.

Regardless of structural system type, having quantitative data on the seismic/structural performance of a building that is to undergo detailed engineering evaluation, or repair/strengthening design, is invaluable to a practicing engineer. Computer models of the building can be calibrated against actual performance increasing the confidence of the predictive analysis regarding performance of the repaired or strengthened building in future earthquakes.

5. Case Studies

Case studies from several buildings are presented here.

5.1. Abu Dhabi SHM Network

After a couple of years of completion of the Abu Dhabi SHM Network, in April 2013, two large earthquakes struck the region of southern Iran. ShakeMaps created by USGS (USGS Earthquake

Hazards Program 2013) and the new Abu Dhabi network for the M7.7 2013-04-16 Sistan-Baluschestan earthquake are shown in Fig 4. Although very far away and producing seemingly low amplitudes of structural response (Safak et.al. 2014), both events resulted in mass evacuations across many Gulf countries including Abu Dhabi. One obvious explanation for the understandable widespread reaction is that the region is simply not use to seismic activity. However, there is an additional possible reason that is revealed through careful examination of the data from the instrumented tall buildings.

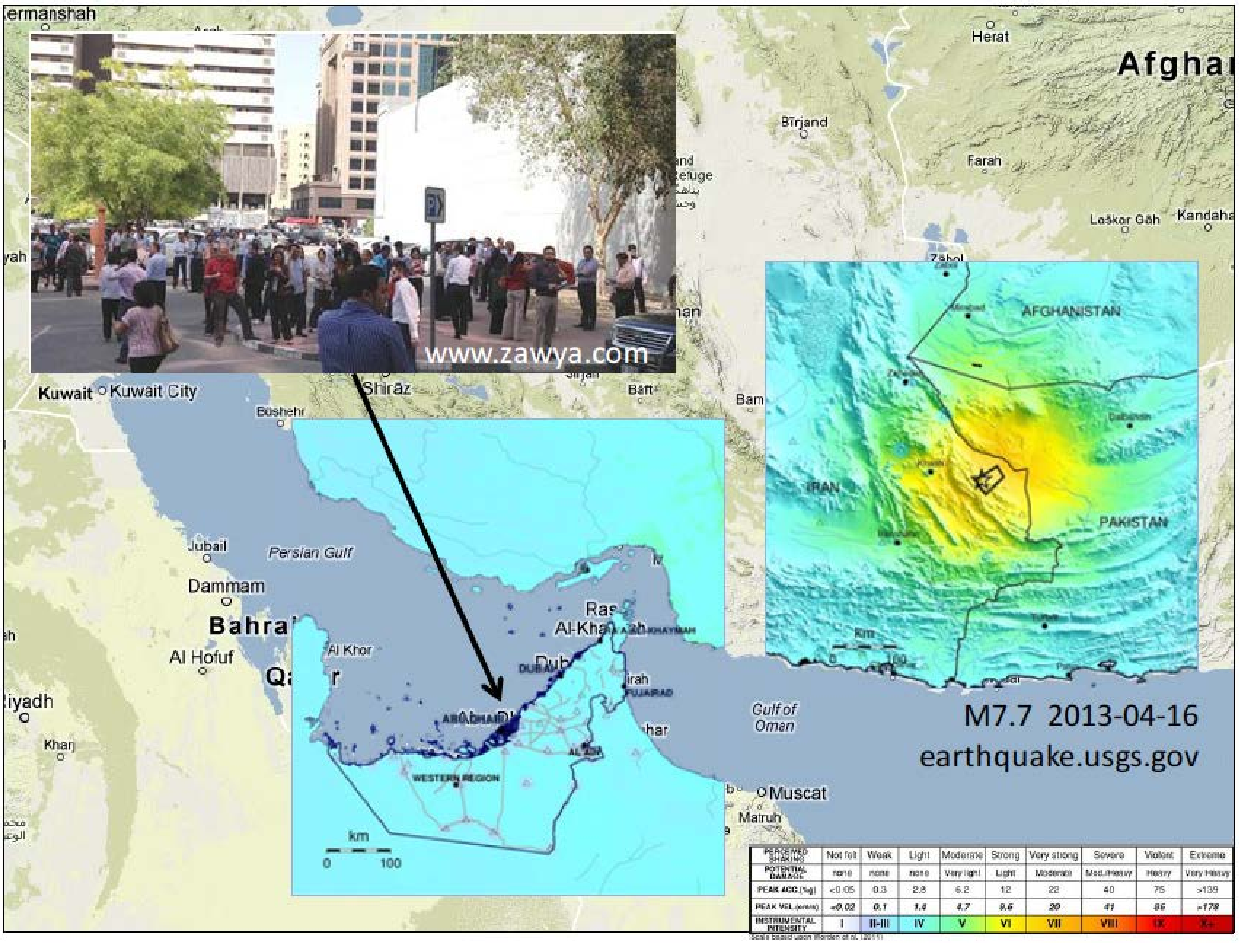

Fig. 4 – ShakeMaps and evacuation from M7.7 2013-04-16 Sistan-Baluchestan Earthquake.

The top right of Fig 5 displays the acceleration history at the top level of a tall building during the M7.7 2013-04-16 event. The acceleration amplitude is quite low, approximately 0.01g, but the shaking does seem to last a long time. To better understand exactly how long the level of shaking persisted above specific levels of human response, the RMS velocity levels in dB are computed for several floors (Hanson 2006). The thermometer scale on the left hand side of Fig 5 correlates the estimated human response to various RMS velocity levels. For example, the threshold of human perception is approximately 65dB whereas the point at which people begin to have difficulty with certain tasks such as reading computer screen is set at 90dB.

From the bottom right plot in Fig 5, it can be seen that for floors 20th and higher, the shaking amplitude was above the threshold of task difficulty (90dB) for more than 10mins, and from the 40th floor and higher, the shaking was above the threshold for human perception for almost one hour! Clearly, such long lasting shaking would bring about discomfort in even the most experienced inhabitants of active seismic regions. See Safak et.al. 2014 for more in depth analysis of structural response for this tall building.

5.2. Dubai SHM Systems

The installation of the structural health monitoring system at the Shaikh Rashid Tower at the Dubai World Trade Center (DWTC), the oldest tower in Dubai, and at Burj Khalifa, the tallest man-made structure in the world has just been completed.

The system at the DWTC will provide red-yellow-green alarms for the on-site security team to take appropriate action after an earthquake. Alerts with automatically generated reports displaying the building response status (Fig 6-left) will be sent to the designated officials to support their emergency response planning decision. A customized response plan based on the unique structural characteristics and ATC-20 post earthquake evaluation procedures was developed as shown on Fig 6-right below. Onsite response team members were trained on the plan and annual testing (similar to fire alarm testing) is expected to be implemented alongside retraining as necessary.

The system alerts and reports will help the safety team decide how and when to evacuate the building and the subsequent decision on when to reoccupy. This will avoid unnecessary evacuation such as those that took place during the April 2013 events. Office towers and other high-rises in Dubai were evacuated and people spent hours in the open due to the impact of earthquakes that shook southern Iran and Northeast of Iranian Balochistan on April 9 and 16, respectively. A repeat of these evacuations occurred again on May 27, 2014 after a 5.1 magnitude earthquake hit southern Iran's Qashem Island, 156 km northeast of Dubai.

News media reports described in detail all the distress created by these events and the prolonged hours of downtime that hotels, office buildings, and others experienced leading to financial losses, not quantified yet but estimated to be significantly high, considering that the DWTC along produces 2.2% of UAE's total GDP.

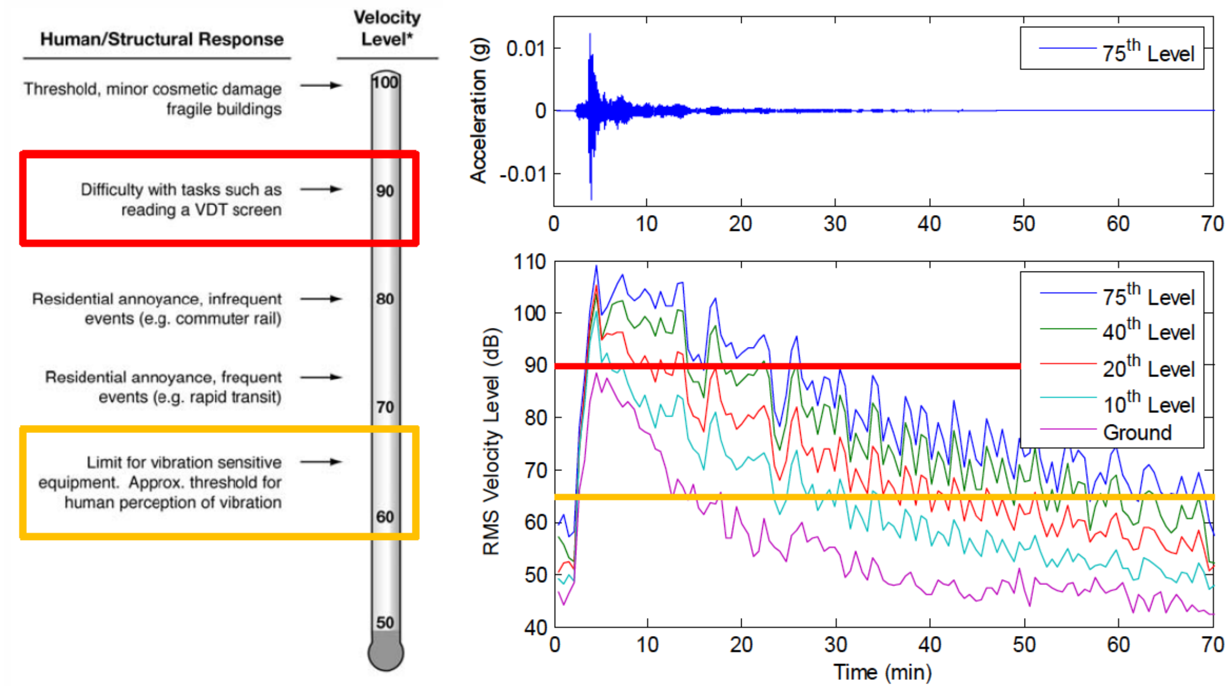

Fig. 5 – Acceleration and vibration levels recorded at various floors of a tall Abu Dhabi building during M7.7 2013-04-16 earthquake with ground-borne vibration level scale.

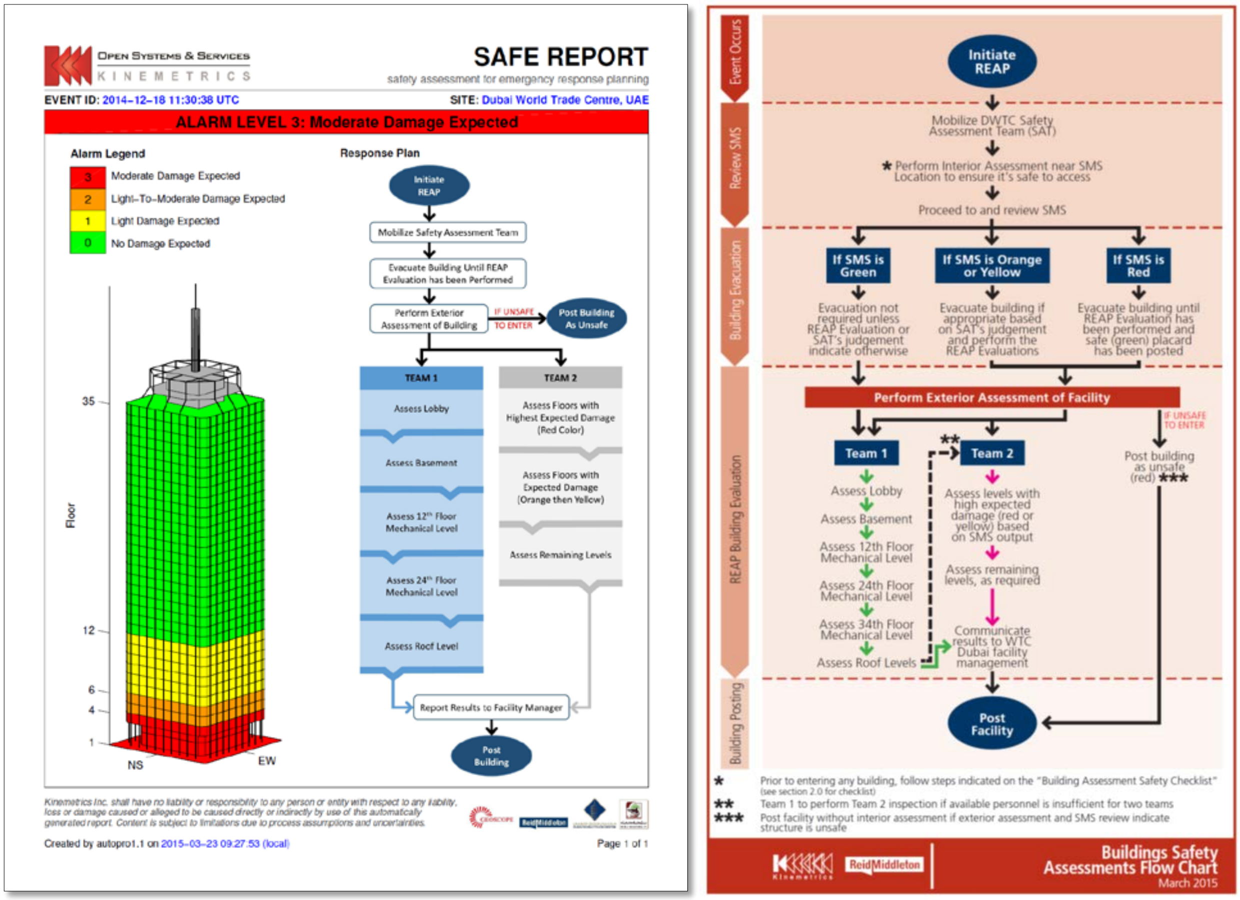

Fig. 6 – DWTC Response Plan showing an automatically generated report (left) and customized ATC-20 based post-earthquake evaluation procedure (right).

6. Conclusions

Structural health monitoring systems, such as Kinemetrics OASIS, provide timely information that can be useful in all phases of post-event response if the information processing is well integrated within the overall PEA plan. Experiences gained through projects such as those presented as case studies here offer invaluable insight into what is required to implement a comprehensive response plan towards enhanced rapid post-earthquake inspection and assessment.

In general, the benefits of implementing a system like this can be summarized as follows:

1. Occupant confidence and safety is improved, avoiding panicked crowds.

2. Building Owners save money by reducing costly downtime and business interruption caused by unwarranted evacuations.

3. Facility Managers are better-equipped to make informed decisions on evacuation and reoccupation.

4. Policy Makers improve safety mandates for the public and showcase city's resilience and growth.

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