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To cite this article: S Toprak *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **800** 012042

IOP Conf. Series: Materials Science and Engineering **800** (2020) 012042 doi:10.1088/1757-899X/800/1/012042

Pipe type and seismic performance in Christchurch, New Zealand

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Abstract. The pipeline damages observed in Christchurch, New Zealand during the 2010-2011 earthquakes provided new insights regarding the seismic performance of pipelines. The water pipeline damages were extensive and water service was interrupted for a long period of time. Meanwhile, unprecedented efforts have been underway following the period right after the first earthquake up to now to obtain and store data related to entire damaged structures, geology, soil conditions, seismicity etc. in the area for the recovery and future planning purposes. These data have been very crucial to study, understand and apply the lessons learnt from these earthquakes and get ready for future earthquakes. This paper focuses on seismic performance of pipelines regarding the pipe type during the M_W 6.2 22 February 2011 Christchurch earthquake. Majority of pipeline damages occurred in soil liquefaction areas where differential settlements and lateral strains affected the pipelines adversely. In addition, liquefaction severity parameters such as liquefaction potential index (LPI) and liquefaction severity number (LSN) have been considered in the evaluations of damages. Pipelines in Christchurch consisted of different pipe materials and their performance during the earthquake differed significantly. Geographical information systems (GIS), clustering analyses (fuzzy and k-means methods) and reliability aspects were used in their assessment.

1. Introduction

Water distribution pipelines are critical part of the infrastructure systems in urban areas. They transmit water for firefighting, drinking, cleaning, industrial and many other uses. Functionality of these water distribution systems or getting them back into the service in short times after the earthquakes are essential for the society. The only way to achieve this objective is to evaluate the systems before any earthquake occurs against seismic actions and take necessary steps to eliminate the deficiencies in the systems. The evaluations have to take into consideration whole aspects the condition of the system, the needs before and after the earthquake, the level of seismic loading, and soil conditions.

The Canterbury earthquake sequence which occurred in 2010-2011 and the respective damage and performance database of Christchurch City has been one of the best documented cases for the earthquakes up to today. The database includes but not limited to seismicity of the area [1], strong ground motions [2], pipeline systems [3], [4], soil investigations [5] and buildings [6]. Toprak presented ground displacement measurements from air photo, satellite, high resolution light detection and ranging (LiDAR), and ground surveys data with respect to their effects on pipeline damage assessments [7]. It is expected the results of the investigations and research related to these databases create new approaches, methodologies and applications to get ready for the future earthquakes. The research presented in this paper focus on buried pipeline systems and their performance during the 2011 Christchurch earthquake.

2. Christchurch pipeline system and earthquake effects

The water pipelines in Christchurch can be considered in two groups as main and submain pipelines. Main and submain pipelines are approximately 1700 km and 2000 km, respectively. The diameter range of main pipelines is between 75-600 mm and conveys the main portion of the water in the system. Because of some reliability problems on submain repairs, only main pipelines and repairs were considered in this study [8]. Figure 1 shows main pipelines in Christchurch. The pipelines are located almost exclusively on road corridors. As described by Cubrinovski [9], [10], the pipelines are laid in trenches 200-300 mm wider than the pipe diameter, at relatively shallow depths. The cover thickness depends on the pipe size, location and material, but is usually about 800mm (at least 750mm, but no more than 1.5m for the standard water mains diameters). Pipe trench characteristics have changed over time. From the first development of the network, trench backfill material was either the locally excavated soil material if soil particle size was appropriate (sands through to fine gravels), otherwise fine gravel material was imported from quarries situated on the city margins. From 1984 trench construction was standardized so that all pipes were emplaced in a sand layer covered with AP40 gravel mix. There was a program of backfill compaction testing to identify the optimum mix to prevent trench settling, which was impacting road surfaces. From 2005 an AP20 gravel mix has been used, as it was determined to be less abrasive and damaging to pipe materials than the AP40.

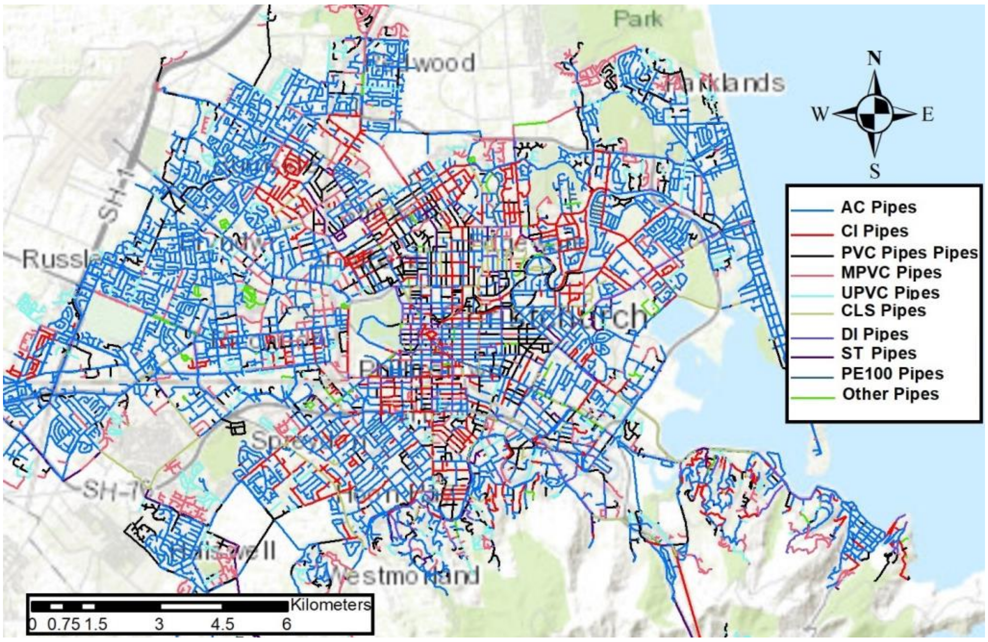


Figure 1. Pipelines in Christchurch with respect to pipe material

The water distribution system consists of various pipe materials. Figure 1 shows geographical distribution of Christchurch water main lines with respect to pipe material by the time the 22 February 2011 earthquake took place. Almost half of the pipelines are asbestos cement (AC) pipelines. Other major pipe types are cast iron (CI), polyvinyl chloride (PVC), modified polyvinyl chloride (MPVC), and unplasticised polyvinyl chloride (UPVC). About 9 % of the pipelines are concrete lined steel (CLS), ductile iron, concrete lined ductile iron (CLDI), steel (ST), and polyethylene 100. Less than one percent of the pipelines consists of polyethylene (PE), medium density polyethylene 80

(MDPE80), medium density polyethylene 100 (MDPE100), high density polyethylene (HDPE), mortar lined ductile iron (MLDI), reinforced concrete rubber ring (RCRR), and galvanized iron (GI).

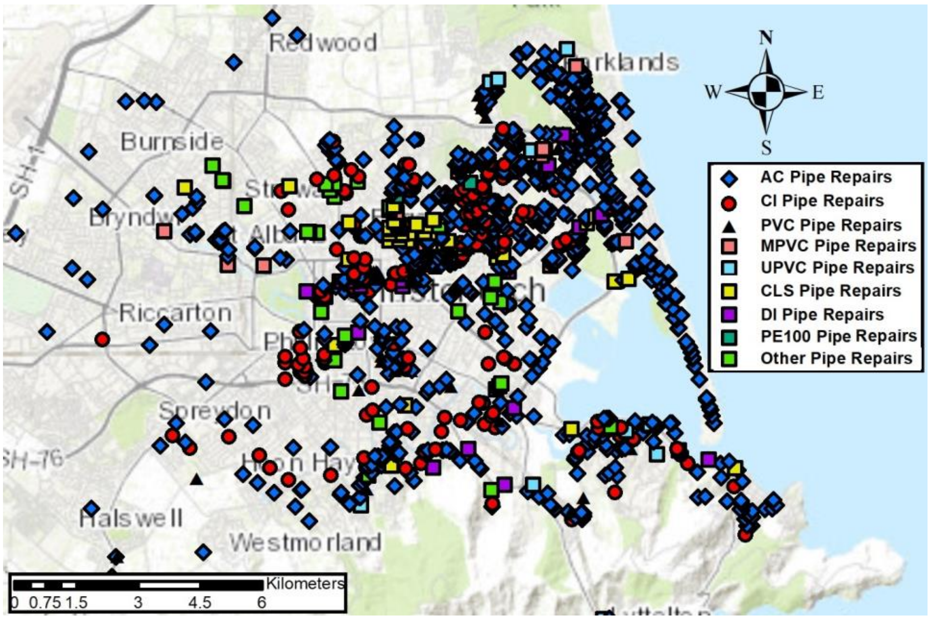


Figure 2. Pipeline repairs in Christchurch with respect to pipe material

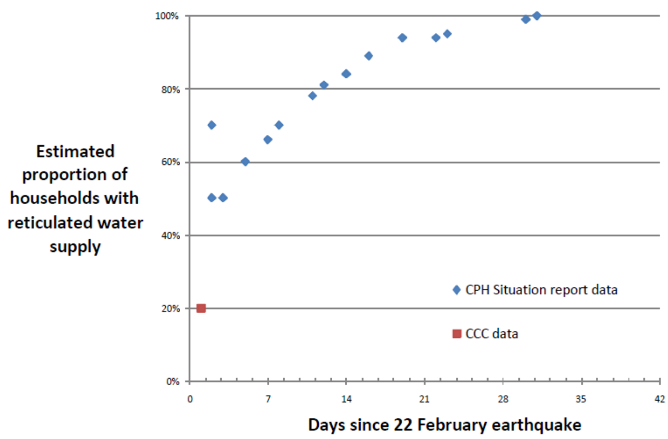
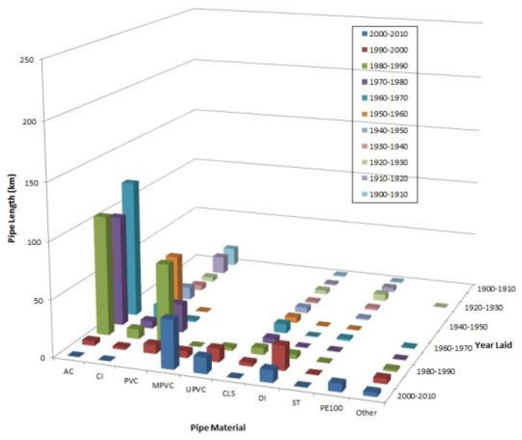
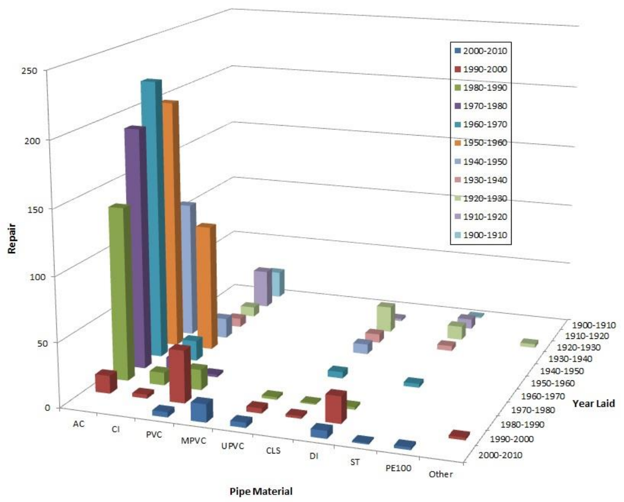


Figure 3. Water service recovery after the 22 February 2011 earthquake. [11]

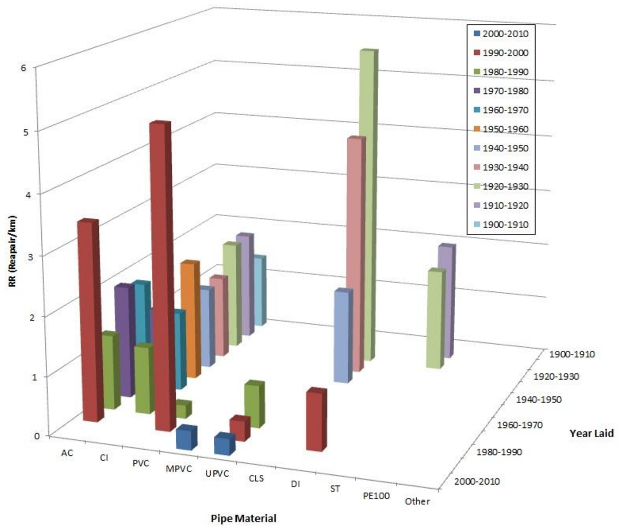
The 22 February 2011 earthquake caused substantial damage to the pipelines (Figure 2). The total number of repairs to main pipelines was 1502. About two thirds of the damages occurred on AC pipelines. As shown in Figure 3, although service was provided to about half of the households a few days after the earthquake, the recovery took significant time. The City applied "boil water notice" to whole Christchurch between February 23rd and April 8th, 2011 to protect residents against disease. The "boil water notice" is about to treat tap or tanker water by boiling before any use for drinking, brushing teeth or preparing food.



a) Length Distribution of Pipelines with respect to pipe material and year of construction



b) Number of repairs corresponding to pipe material and year of construction



c) Repair rate corresponding to pipe material and year of construction

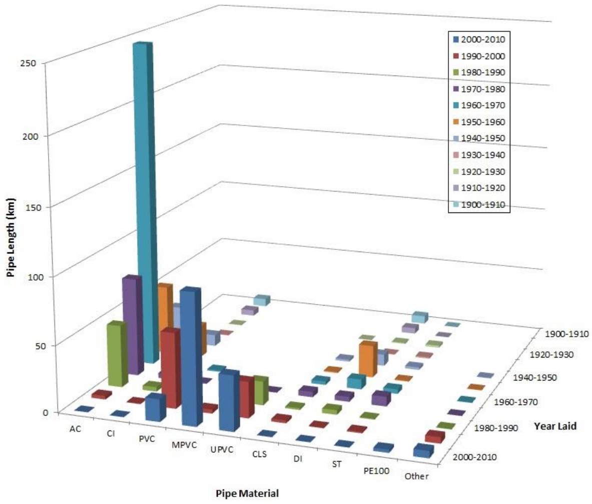
Figure 4. Pipelines in liquefaction zone with respect to pipe material and year of construction

3. Evaluation of Performance

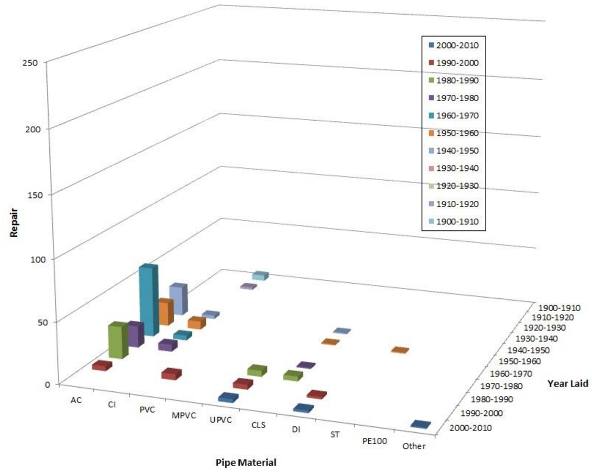
One of the main characteristics of the 22 February 2011 earthquake was the extent of the soil liquefaction and its damage in Christchurch. Buried pipelines like buildings were affected by extensive liquefaction. Because the seismic actions are different inside and outside the liquefaction zones, their analyses performed separately. Pipelines in the liquefaction areas are affected by permanent ground deformations such as lateral or vertical displacement whereas the pipelines out of liquefaction zones are subject to ground shaking effects. Therefore, both cases should be considered separately for the assessment of pipeline damages.

Geographical information systems (GIS) were utilized during the preparation of the database and analyses stage. Figures 4a, 4b, and 4c show, respectively, the length in km, number of repairs and repair rate of pipelines in the liquefaction zone with respect to pipe material and year of construction.

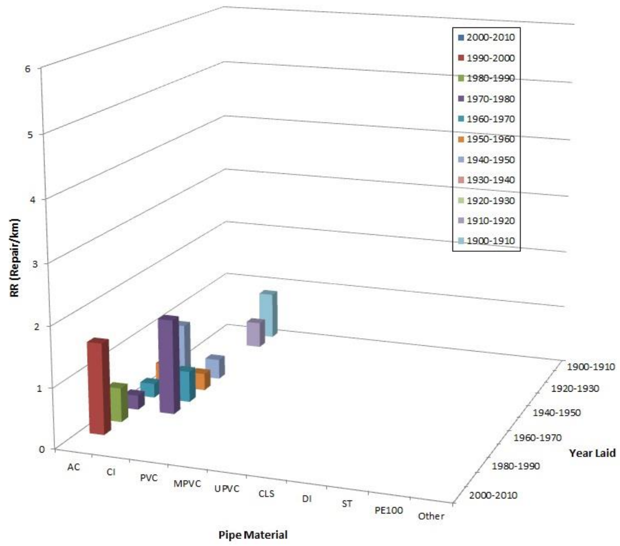
Most of the pipelines were constructed after 1940s. Installments of AC and CI pipelines stopped even before the earthquake. Polyethylene pipelines were the preferred pipe type for the replacements after the earthquake. Repair rate (RR) is commonly used in pipeline damage assessment studies and shows the number of repairs divided by the length of the pipelines in the same area. In essence, the number of repairs are normalized by length of pipelines. It should be noted that not all RR values are shown in Figure 4c, because a screening criteria was applied. The fidelity of the RR statistics is sensitive to the pipeline length sampled and number of repairs observed within a given sampling length. Hence, in this study, the screening criteria developed by O'Rourke [3] were used during the RR analysis of pipeline damage to ensure fidelity of the RR comparisons.



a) Length Distribution of Pipelines with respect to pipe material and year of construction



b) Number of repairs corresponding to pipe material and construction year of pipeline

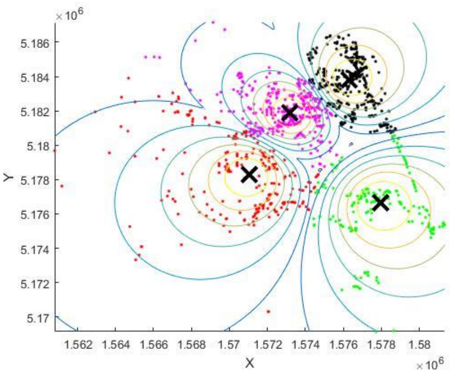


c) Repair rate corresponding to pipe material and construction year of pipeline

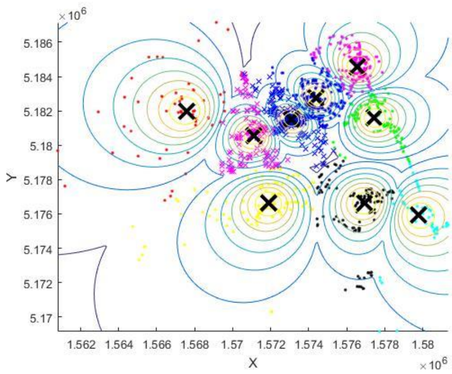
Figure 5. Pipelines in non-liquefaction zone with respect to pipe material and year of construction

Figures 5a, 5b, and 5c show, respectively the length in km, number of repairs and repair rate of pipelines in the non-liquefaction zone with respect to pipe material and year of construction. It should be noted that Figure 5c shows the RR values only for the pipelines which pass the screening criteria explained above. Comparison of figures clearly shows that the repair rates are much higher in the liquefaction zone. Also AC pipelines performed worse compared to other pipelines. The spatial trends and pipe material effects in pipeline repairs can be analyzed by using clustering techniques. This method previously applied to City of Los Angeles water pipelines damaged by the 1994 Northridge earthquake [12]. An application of the k-means clustering analyses to Christchurch water pipeline damage data provided promising results [13]. Another method, fuzzy c-means clustering technique, is also one of the powerful methods which has been utilized in the analyses of pipeline damage in Christchurch (Figure 6).

Although pipe material type and pipeline instalment year are important for the seismic performance of pipelines, they are not the only factors that control the pipe behavior. The magnitude and the extent of seismic loading can be critical as well. The level of shaking in non-liquefaction zones and the level of ground deformations in liquefaction zones can force the pipeline to failure. For example, O'Rourke [3] and Toprak [7] utilized lateral strains and ground deformation parameters when developing pipeline damage correlations in liquefaction zones and ground velocity parameter (GMPGV) when developing pipeline damage correlations in non-liquefaction zones. Toprak [4] proposed the first time the use of liquefaction severity parameters in pipeline damage correlations and provided respective relationships. Those relationships are expected to contribute to loss estimation studies for urban areas. Figure 7 shows such a relationship only for one of the liquefaction vulnerability parameters, liquefaction severity number (LSN).



a) 4 clusters



b) 9 clusters

Figure 6. Fuzzy c-means clustering application to Christchurch pipe repairs.

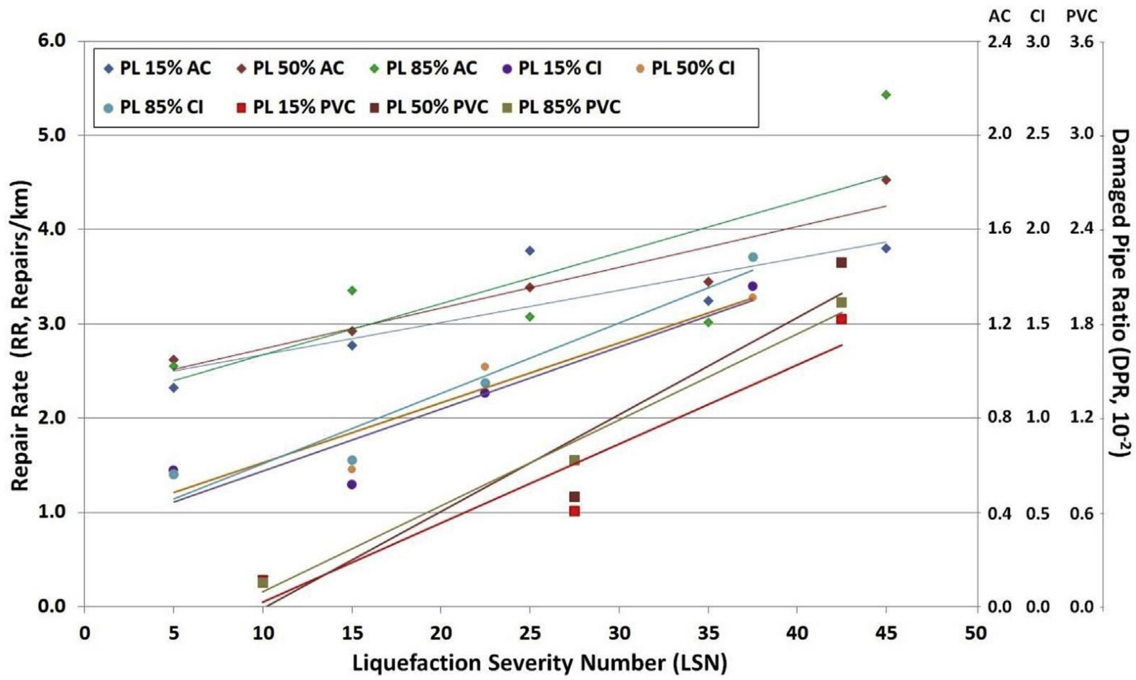


Figure 7. RR and DPR vs. LSN relationships for AC, CI, and PVC pipelines and probabilities of liquefaction of 15%, 50%, and 85%. [4]

4. Conclusions

The pipeline damages occurred during the Canterbury earthquake sequence provided unprecedented opportunity to evaluate seismic pipeline performance particularly in liquefaction zones and make recommendations for future applications. Within the scope of the research activities of the authors of this paper and collaborators, characteristics and performances of the damaged and undamaged pipelines have been investigated both in liquefied and non-liquefied areas in Christchurch and new pipeline damage correlations were proposed. The results show that AC pipelines have the highest damage rates, significantly higher than that for PVC pipelines. CI damages are about the average of AC and PVC pipelines. The ongoing studies focus on probabilistic and reliability assessment of pipelines along with clustering applications.

Acknowledgments

The Scientific and Technological Research Council of Turkey (TUBITAK) supported the research presented herein under Project No. 114M258. PAU BAP support was under Project No. 2019FBE013. The Christchurch Earthquake Recovery Authority (CERA), Stronger Christchurch Infrastructure Rebuild Team (SCIRT), Christchurch City Council (CCC), Earthquake Commission (EQC), Contact Energy are acknowledged for their assistance.

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