SOURCE CHARACTERISTICS AND TECTONIC IMPLICATIONS
OF MODERATE EARTHQUAKE,
NORTHEASTERN CAIRO PREFECTURE

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Abstract

Using local seismograms of the Egyptian National Seismological Network (ENSN), source characteristics of a moderate earthquake $M_w = 4.5$ (28 December 1999) are analyzed. In this analysis, the Empirical Green’s Function (EGF) deconvolution technique is applied. The records of an appropriate aftershock are taken as the EGF and are used to deconvolve the mainshock seismograms, thus obtaining a Relative Source Time Function (RSTF) at each station. The deconvolution is performed using $P$ waves in frequency domain. From the time-domain analysis of the RSTF, the resulting source time functions indicate a simple rupture process. The azimuthal dependencies of the RSTF pulse amplitudes and widths are used to estimate rupture velocity and rupture direction for the mainshock. The azimuth of rupture direction is obtained using a global optimization method. We found that the rupture direction of the main event propagated toward S175°E with an averaged rupture velocity around 0.75 $V_s$. The result obtained for rupture direction is in agreement with one of the nodal planes of focal mechanism. From the rupture directivity analysis, focal mechanism and geological evidence it follows that the investigated event reflects a reactivation of a NW-SE Oligocene deep-seated normal faulting with sinistral movement. Source parameters were estimated using RSTFs of the mainshock, including seismic moment of $2.85 \times 10^{15} \text{N} \cdot \text{m}$, fault radius of 344 m, fault length 1460 m, and static stress drop of 3.071 MPa.

Key words: Empirical Green’s Function, relative source time function, source parameters, tectonic implications.
1. INTRODUCTION

Detailed analysis of small earthquakes reveals that they occur with a variety of rupture modes and rupture velocities similar to large earthquakes (Frankel et al., 1986; Mori and Frankel, 1990; Li et al., 1995; Imanashi and Takeo, 2002). For this reason, it is important to understand how the rupture mode changes over a wide range of earthquake sizes in order to elucidate the generating mechanism of earthquakes. Because of the lack of observations, it is difficult to determine for small-size earthquakes the distribution of aftershocks that clearly define the fault plane. For strike-slip events with source dimensions of a few meters to kilometers, the fault plane determination based on the rupture directivity criteria should be possible because the horizontal directivity effects due to finiteness of the source would be significant for the two nodal planes. Using a small earthquake as an Empirical Green’s Function (EGF) to isolate the complicated path and site effects from observed seismograms, the source time function (STF) of a given earthquake can be extracted (Hartzell, 1978). The extracted STF contains information on the important parameters that characterize both the rupture process and source properties of the earthquake. Analysis of the STF reveals the rupture complexity and rupture directivity of small earthquakes (e.g., Frankel et al., 1986; Li and Thurber, 1988; Mori and Frankel, 1990; Abdel-Fattah and Badawy, 2002). The retrieved STF also demonstrated that the rupture directivity along with the focal mechanism of an earthquake could be used to determine which of the two nodal planes is the fault plane (Mori and Hartzell, 1990; Mori, 1993; Badawy and Abdel-Fattah, 2001).

On Tuesday, 28 December 1999, a small earthquake sequence took place in northern Egypt, about 25 km northeast of Cairo. The $M_w = 4.5$ mainshock was felt throughout the great Cairo region and 12 minutes later was followed by $M_w = 3.9$ aftershock and 4 hours later by $M_w = 3.6$ aftershock. In reality, the earthquakes in northern Egypt tend to occur as isolated sequence (Abdel-Fattah et al., 1997). Interesting sequences, not only the observed one, but many others (29 April 1974, 2 January 1987, 14 December 1987, 22 May 1992, 19 November 2001) were reported as well.

In the present study, the $P$-waveform data are analyzed in detail to extract RSTF using EGF deconvolution approach and thus investigating the characteristics of the rupture process of the respective event. Then, we finally combined the obtained results for seismotectonic interpretations.

2. SEISMOTECTONIC CONTEXT

The spatial distribution of earthquake epicenters in Egypt (Fig. 1) suggests that the main activity occurred in northern part of the Egyptian territory. The relative motion of the Sinai subplate with respect to the Arabian plate (Gulf of Aqaba and Dead Sea) and to the African plate (Gulf of Suez) represents the main source of active tectonics and seismic activity. Moreover, it can be considered as a direct seismotectonic consequence of the Sinai subplate kinematics (Badawy, 1996; 1998; Badawy and Horváth,
On the basis of earthquake distribution, Egypt can be divided into the two tectonic provinces: northern Egypt (north of 27°N) and southern Egypt. The first province is more seismically active than the second province. It was also demonstrated that these provinces differ in stress patterns too (Badawy, 2001a,b).

Moreover, the general distribution of earthquake epicenters falls into three major trends. The first trend (Clysmic) extends from the Gulf of Suez through the cities of Cairo and Alexandria. The activity along this trend is mainly attributed to the Red Sea rifting and characterized by shallow earthquakes and microearthquakes (Kebeasy, 1990). The second trend (Pelusiac) extends from the eastern Mediterranean Sea to the southeast Cairo and Fayoum region. Along this trend, small to moderate historical and recent earthquakes have been observed. Along the Aqaba Levant trend (the third one), the seismic activity is highly related to the Gulf of Aqaba–Dead Sea fault system. The investigated event and many remarkable earthquakes (29 April 1974, 2 January 1987, 14 December 1987, 22 May 1992, 19 November 2001) took place along the first trend.
The first trend intersects the second one at Cairo city. Within this intersection, the moderate earthquake of 12 October 1992 \((Mb = 5.9)\) has occurred. Since the occurrence of this event, the Cairo region has been the focus of intense geological and geophysical investigations.

A modern digital short-period seismograph network was established around Cairo in order to monitor local and regional earthquake activity. Figure 2 depicts earthquake activity around Cairo from 1997 to 2001. From Figs. 1 and 2 it is clear that the Cairo region has suffered not only from interplate earthquakes but also from inland seismic dislocations. The most active inland dislocation is the Dahshour area (25 km southwest Cairo). Also the scattered activity to the east and northeast-east of Cairo has been observed. Gulf of Suez is thought to be the only well defined plate boundary between Africa and Sinai subplate (Ben-Menahem \textit{et al.}, 1976; Joffe and Garfunkel, 1987; Badawy, 1996; Badawy and Horváth, 1999a, b). However, the northwest extension of the Suez rift is still doubtful. Indeed the seismic activity (west to the Gulf of Suez) follows the structural trend of the Suez rift and may continue more northerly toward the investigated source. Also the surface geology supports the occurrence of

![Seismotectonic map of the area around Cairo. ENSN earthquake data file from 1900 to 2001 is shown. The fault trace is redrawn from the Egyptian Geological Survey (1981).](image-url)
earthquakes along different fault segments mainly parallel to the rift trend (Fig. 2). More dense local earthquake data and the increasing stress accumulation will support the idea that one of these segments may delineate the actual northward extension of the boundary. The present-day stress field, estimated from several focal mechanisms and borehole breakouts (Badawy, 2001a, b), shows a transtensional stress regime with a tension axis about N-S to NE-SW in northern Egypt. Three fault trends, E-W, NW-SE, and NE-SW, affect the epicentral area. All these faults are normal faults. The stresses which created the structure in the investigated area were tensional rather than compressional (Shukri, 1953; Said, 1962).

3. DATA AND EMPIRICAL GREEN’S FUNCTION DECONVOLUTION

Waveform data used in this study are from five stations belonging to the Egyptian National Seismograph Network (ENSN). All instruments are velocity sensors with a 24-bit digital recording system with sampling rate of 100 sample/s. The instrument response is flat, from 1.9 to 38 Hz. The dynamic range is of about 124 dB. For waveform analysis, we used only the P-wave part of velocity records. The locations of the mainshock, two aftershocks and the seismic stations used in the analysis are shown in Figure 3. The focal parameters of mainshock and two aftershocks are listed in Table 1. The capital letters M, Af1 and Af2 correspond to the mainshock and its two after-
shocks, respectively. Using the waveform cross-correlation, relative location and focal mechanism, Badawy and Abdel-Fattah (2001) identified the three events as a multiplet. This earthquake sequence yields an amount of good waveform data providing a unique opportunity to use the Af2 as EGF to study the physical process of moderate earthquake.

Table 1
The hypocentral parameters of the earthquake sequence of 28 December 1999
(from Badawy and Abdel-Fattah, 2002)

<table>
<thead>
<tr>
<th>Event</th>
<th>Origin time</th>
<th>Latitude (°)N</th>
<th>Longitude (°)E</th>
<th>Depth [km]</th>
<th>$M_L$</th>
<th>$M_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>12$^h$05$^m$11.10$^s$</td>
<td>30.2336</td>
<td>31.4703</td>
<td>19.1</td>
<td>4.4</td>
<td>4.5</td>
</tr>
<tr>
<td>Af1</td>
<td>12$^h$17$^m$42.73$^s$</td>
<td>30.1886</td>
<td>31.4890</td>
<td>19.3</td>
<td>3.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Af2</td>
<td>16$^h$29$^m$08.55$^s$</td>
<td>30.2042</td>
<td>31.5070</td>
<td>16.8</td>
<td>3.3</td>
<td>3.6</td>
</tr>
</tbody>
</table>

In this study, the analysis of waveform data is based on the idea that the seismogram from a small nearby earthquake can be used as an EGF to extract the RSTF of a large earthquake. The assumption of the method is that the source of the small event can be viewed as a point source, so that there is no source contribution in the seismogram except for the focal mechanism which must be similar to that of the large earthquake. The advantage of using the waveform of the small earthquake as an EGF is that detailed knowledge of the earth structure, instrument response, attenuation and site effects is not required. Since the pair of events is recorded at the same station by the same instrument and shares the same propagation path, the deconvolution method should result in an RSTF that is corrected for the path, site and instrument effects. The observed seismogram is the result of a convolution of the source time function $S(t)$, the path effect $Q(x,t)$, recorded site effect $R_s(t)$ and instrument response $I(t)$. Following Mueller’s (1985) method, for two earthquakes with the same hypocenter and different magnitude, recorded at the same station, the observed seismograms are given by

\[
U_L(x,t) = S_L(t) \ast Q(x,t) \ast R_s(t) \ast I(t),
\]
\[
U_S(x,t) = S_S(t) \ast Q(x,t) \ast R_s(t) \ast I(t),
\]

where $U_L(x,t)$ and $U_S(x,t)$ are the records of the large event and the small event, respectively, and $\ast$ is the convolution operator. Using empirical Green’s event, the deconvolution of the mainshock is performed by spectral division in the frequency domain. The spectral amplitudes of the large and small earthquakes are given by

\[
U_L(x,w) = S_L(w) \cdot Q(x,w) \cdot R_s(w) \cdot I(w),
\]
\[
U_S(x,w) = S_S(w) \cdot Q(x,w) \cdot R_s(w) \cdot I(w).
\]
Fig. 4. The $P$-waveforms of the mainshock and two EGF recorded at five ENSN stations, along with the RSTF estimates. The maximum amplitude is shown for each record.
If the two earthquakes have the same mechanism, they have the same radiation pattern. The difference between the two signals is only due to the source time function. If the Green function of the event is small enough and its signal to noise ratio is appropriated, then we can consider its source time function as a Dirac delta function.

Then the result of deconvolution is

\[
\frac{U_s(x,w)}{U_s(x,w)} = \frac{S_s(w) \cdot Q(x,w) \cdot R_s(w) \cdot I(w)}{S_s(w) \cdot Q(x,w) \cdot R_s(w) \cdot I(w)} = \frac{S_s(w)}{S_s(w)} = \frac{S_s(w)}{\delta(w)} = S_s(w). \tag{3}
\]

The source time function of the mainshock event is obtained after taking the inverse Fourier transform of \(S_s(w)\).

After obtaining the RSTFs, a Butterworth low-pass filter with corner frequency of 30 Hz was used to reduce the high frequency noise. The noise may be caused by the variation of background noise at the stations, the spatial separation between the large and EGF events, and the finiteness of the source time function of the EGF event (Frankel et al., 1986; Li and Thurber, 1988). The obtained source time functions can be used to detect directivity effects by considering the differences of their shape at different stations. The \(P\)-waveform data for the mainshock and the Af2 as well as the corresponding deconvolved source time functions are shown in Fig. 4.

4. DIRECTIVITY ANALYSIS

Amplitude and pulse width of the STF reflects the azimuthal dependence of the radiation of body waves from extended seismic sources (e.g., Ben-Menahem, 1962). For unilateral rupture at the same distance from the earthquake seismic zone, the source duration is narrowest in the direction of rupture propagation and widest in the opposite direction. Due to the same effect, the amplitude of the STF in the rupture direction is larger than that in the opposite direction. The velocity and the rupture propagation direction can be determined simultaneously by the least-squares technique either from the distribution of the RSTF pulse width (e.g., Li and Thurber, 1988) or from the distribution of their maximum amplitudes (Li et al., 1995). For a finite moving source, the relation between the pulse width \(\tau\) and the azimuth angle \(\phi_0\), measured from the propagation direction can be written as (e.g., Ben-Menahem, 1962)

\[
\tau = a - b \cos(\phi - \phi_0), \tag{4}
\]

where \(a = L/V_r, \quad b = L/V_p\) and \(L\) is the fault length, \(V_r\) and \(V_p\) are the rupture and \(P\)-wave velocity, respectively, and \(\phi\) is the station azimuth.

Following Abdel-Fattah (2003), we used simulated annealing to obtain the model parameters representing eq. (4). Simulated annealing was first introduced as an intriguing technique for optimizing functions of many variables (Kirkpatrik et al., 1983). In the standard iterative methods, a series of trial points is generated until an improvement in the objective function is noted in which case the trial point is accepted.
However, this process only allows for downhill movements to be made over the domain. This has often led to a local minimum. Simulated annealing is a global optimization method that distinguishes between different local optima. Starting from an initial point, the algorithm takes a step and the function is evaluated. In trying to reach a function minimization, simulated annealing moves uphill and downhill. Any downhill step is accepted and the process repeats from this new point. An uphill movement may be accepted. Thus, it can escape from local optima. The acceptance of uphill decision is made by following a probabilistic manner described in Metropolis et al. (1953) in the form of

$$ P = \exp \left( -\frac{f_i - f_0}{T} \right), $$

where $f_i$ is the observed pulse width or the reciprocal amplitude of RSTF and $f_0$ is the calculated one.

When the temperature is high, the probability distribution is almost insensitive to the misfit function and any value can be chosen. When the control parameter $T$ decreases, few models remain acceptable and when the system is frozen, only the solution providing the smallest misfit function is kept. A fall in control parameter is imposed upon the system with the $\lambda$ variable by $T_{i+1} = \lambda T_i$, where $i$ is the $i$-th iteration. As a temperature declines, the method permits to avoid local minimum of the objective function and allows reaching the global minimum in a reasonable number of iterations.

The rupture direction is estimated by fitting the pulse duration at stations with different azimuths to obtain a best straight line. Then the slope and intercept of this straight line are used to estimate the rupture velocity and the fault length. A similar procedure can be applied to the distribution of pulse maximum amplitudes to estimate the rupture direction and the rupture velocity independently (e.g., Li et al., 1995). The

![Fig. 5. The best fit of the pulse widths of relative source time functions against the cosine of the difference between the station azimuth for the mainshock.](image-url)
best fit of such a procedure for the pulse widths of relative source time functions against the cosine of the difference between the station azimuth and the rupture propagation is shown in Fig. 5 and that for the pulse maximum amplitudes is presented in Fig. 6. Both procedures provide similar results. Source parameters calculated from the investigated event are listed in Table 2, where standard deviation related to the best straight line is also given. The $P$-wave velocity in the source area equal to 6.5 km/s was accepted for calculation. We also applied the global optimization method on the bilateral rupture mode and we found that the closest fits are obtained for the unilateral rupture mode.

### Table 2

Results derived from the analysis of source time functions of the mainshock.

<table>
<thead>
<tr>
<th>Azimuth $\phi_0$ [deg]</th>
<th>$V_r/V_s$</th>
<th>Fault length $L$ [m]</th>
<th>Standard deviation $\sigma$</th>
<th>Seismic moment $M_0$ [N m]</th>
<th>Fault radius $R$ [m]</th>
<th>Stress drop $\Delta\sigma$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>177</td>
<td>0.674</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Pulse width</td>
<td>173</td>
<td>0.772</td>
<td>1459</td>
<td>0.012</td>
<td>–</td>
<td>2.85×10^{15}</td>
</tr>
<tr>
<td>Source parameters</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.85×10^{15}</td>
<td>344.0</td>
<td>3.07</td>
</tr>
</tbody>
</table>

### 5. RELATIVE LOCATION

The pulse widths of RSTFs have been used to estimate the relocation of termination point (barrier) relative to the nucleation point of the mainshock by two different ways. Firstly, the pulse width was added to the arrival times and the relative location was determined using HYPOINVERSE program (Klein, 1985). Secondly, the results of rup-
ture directivity analysis (fault length and rupture direction) have been used to calculate the theoretical pulse width of STFs using the crustal velocity model given in Table 3.

### Table 3

Four-layer crustal velocity $V_p$ model for Northeastern Desert, Egypt (Marzouk, 1988). Ratio $V_p/V_s$ is the rupture velocity over shear-wave velocity.

<table>
<thead>
<tr>
<th>$V_p$ [km/s]</th>
<th>Depth [km]</th>
<th>Thickness [km]</th>
<th>$V_p/V_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>3</td>
<td>13</td>
<td>1.73</td>
</tr>
<tr>
<td>6.5</td>
<td>16</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td>31</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

It is important to note that the rupture velocity has a significant role during these calculations. The observed pulse widths and those calculated from the two relative locations 1 and 2 in Fig. 3 are listed in Table 4. The relative locations of the barrier points (1 and 2) and aftershocks, which lie to the south of the mainshock, reflect unilateral rupture propagation. This means that the inland earthquake activity north of Gulf of Suez tends to occur in NW direction confirming the first trend suggested by Kebeasy (1990).

### Table 4

The observed and calculated pulse widths $\tau$ (in s) at different stations.

- $\phi$ is the station azimuth, $T_p$ is the travel time of the barrier point,
- $t_r$ is the rupture time equal to 0.43 s calculated from directivity analysis.

<table>
<thead>
<tr>
<th>Station code</th>
<th>$\Delta$ [km]</th>
<th>$\phi$</th>
<th>Travel time of the initial rupture point</th>
<th>Obser. $\tau$</th>
<th>Hypoinverse $T_p$</th>
<th>$T_p + t_r$</th>
<th>$\tau$</th>
<th>Directivity analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>KOT</td>
<td>46.44</td>
<td>46.44</td>
<td>8.81</td>
<td>0.17</td>
<td>8.60</td>
<td>09.03</td>
<td>0.22±0.05</td>
<td>8.62</td>
</tr>
<tr>
<td>AYT</td>
<td>64.34</td>
<td>64.34</td>
<td>11.51</td>
<td>0.17</td>
<td>11.31</td>
<td>11.74</td>
<td>0.23±0.06</td>
<td>11.31</td>
</tr>
<tr>
<td>FYM</td>
<td>71.13</td>
<td>71.13</td>
<td>12.53</td>
<td>0.18</td>
<td>12.35</td>
<td>12.78</td>
<td>0.25±0.07</td>
<td>12.34</td>
</tr>
<tr>
<td>SQR</td>
<td>45.49</td>
<td>45.49</td>
<td>8.61</td>
<td>0.17</td>
<td>8.44</td>
<td>08.87</td>
<td>0.26±0.09</td>
<td>8.43</td>
</tr>
<tr>
<td>MYD</td>
<td>79.65</td>
<td>79.65</td>
<td>13.75</td>
<td>0.27</td>
<td>13.64</td>
<td>14.07</td>
<td>0.32±0.05</td>
<td>13.63</td>
</tr>
</tbody>
</table>
6. SOURCE PARAMETERS

In this study, we used the EGF method to estimate the source parameters for the 28 December 1999 northeastern Cairo prefecture earthquake of $M_w = 4.5$. Since the EGF event had a focal mechanism similar to that of the larger event (Badawy and Abdel-Fattah, 2001), we used the seismic moment of the EGF event $M_{0g}$ to calculate the seismic moment for the mainshock. The seismic moment of the large event is estimated by

$$M_o = A M_{0g} ,$$

where $A$ is the average area under the RSTFs. The rise times $\tau_{1/2}$ were measured from RSTFs at different stations and averaged to estimate the fault radius using the relationship given by Boatwright (1980) for a circular source,

$$r = \frac{\tau_{1/2} V_r}{1 - (V_r/V_s) \sin \theta} ,$$

where $V_s$ is the shear wave velocity and $\theta$ is the take-off angle assumed to be 45°. The ratio of the rupture velocity over shear wave velocity, $V_r/V_s$, is taken from the obtained results of directivity analysis. The static stress drop $\Delta \sigma$ is determined from the seismic moment and the fault radius using Brune’s (1970) formula,

$$\Delta \sigma = \frac{7M_o}{16r^3} .$$

The calculated source parameters (seismic moment $M_o$, fault radius $R$ and stress drop $\Delta \sigma$) are presented in Table 2.

7. DISCUSSION AND CONCLUSIONS

In the respective sequence, to ensure that the main event and its two aftershocks had similar source mechanisms, Badawy and Abdel-Fattah (2001) checked cross-correlation, focal mechanisms and the P-polarities for the three events at the ENSN recording stations. Using EGF deconvolution technique in the frequency domain, the RSTF of the mainshock was retrieved. From time domain analysis of RSTF of the main event, the obtained source time functions indicate a simple pulse. Although the azimuthal coverage of the stations is distributed toward the south of the mainshock location, the azimuthal dependencies of the RSTF pulse amplitudes provide evidence to the rupture directivity. Estimates of the model fit using a global optimization method give a rupture direction of about S175°E and averaged rupture velocity of about 0.75 $V_s$. The estimated rupture direction is consistent with the one of the nodal plane of the focal mechanism (NW-SE).
The obtained results allow us to propose a seismotectonic interpretation of the northeastern Cairo \(M_w = 4.5\) earthquake. We suggest that this event is representative of a reactivation of old deep-seated Oligocene NW fault trend that is parallel to the Gulf of Suez. It also confirms the northward continuation of seismic activity that extended from the Gulf of Suez to the epicentral area. This conclusion was drawn on the basis of:

– the fact that one of the nodal planes of the best-determined focal mechanism solution is S137E;
– the probable directivity after EGF analysis (S175E), that is consistent with the result obtained by Badawy and Abdel-Fattah (2001);
– fault traces near the epicenter (Fig. 2); and
– the relative location of both aftershocks and barriers (Fig. 3).

It is worth to note that this moderate-size earthquake occurred on a short fault segment that has no surface expression and was not previously recognized as active: this means that other mapped faults in the area could also have an important seismogenic potential in the future. This fact must be considered when evaluating the seismic hazard in Cairo, which is characterized by high-density population and relatively poor-quality constructions.

As a matter of fact, the operation of modern ENSN made it possible to recover new seismo-active trends and inland dislocations. Therefore, an optimization of ENSN according to the new discovery becomes one of the most important steps in the improvement processes.

The source parameters were estimated from the derived RMRF’s of the mainshock, including seismic moment of \(2.85 \times 10^{15} \text{ N} \cdot \text{m}\), fault radius of 344 m, fault length 1126 m, and static stress drop of 3.07 MPa. These parameters agree well with values that were obtained by spectral analysis technique (Badawy and Abdel-Fattah, 2001) for the northeastern Cairo earthquake sequence and also for earthquakes in northern Egypt (Badawy, 1995; Badawy and Mónus, 1995; Badawy and Abdel-Fattah, 2002). According to Scholz (1990)’s classification of intraplate earthquakes and the obtained source parameters, the respective event could be considered as a type II intraplate that is tectonically related to plate boundaries.

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