Analysis of Asteroid Mass Influences Ocean Impact

Problem B: Asteroid Ocean Impact

Team 385

November 7, 2021

Abstract

Among the plentiful effects caused by asteroids hitting the ocean, tsunami is probably the most devastating type of damage for asteroids. [1]We suppose that the biggest factor causing urban substantial damage is tsunami. Then we divide the course of asteroid hitting the ocean into three processes. Based on the processes, we build physical models to solve the minimum mass of an asteroid that causes substantial damage to a city.

The first process is that the asteroid travels through the Earth's atmosphere to the sea surface. During this process, its speed and mass will be slightly lost. Establishing a physical model can calculate the speed and mass loss of the asteroid.

The second process is that the asteroid hitting the sea causes a tsunami wave. Establishing a physical model can create a connection between the asteroid's kinetic energy and the amplitude of the tsunami wave.

The third process is the propagation of tsunami waves from the deep sea area to the shore. Since the tsunami wave propagates from the deep sea area to the shallow sea area, there is a "Shallow Water Effect", that is, the tsunami wave will increase as it propagates. Establishing a physical model can calculate the amplitude of the tsunami wave reaching the shore.

Finally, we solve the problem in reverse based on the physical models. First, we get the amplitude of the tsunami wave reaching the shore from the level of the tsunami that caused substantial damage. Then we calculate the amplitude of the tsunami wave at 1,000 kilometers. Then we calculate the kinetic energy of the asteroid. Finally we calculate the minimum mass of the asteroid is 4.046×10^{10}kg.

Contents

1 Introduction

The impact of asteroids on the earth will threaten the survival of mankind. After entering the earth, asteroids may hit the earth's land or ocean. Because the ocean area is larger than the land area, the probability of asteroid hitting the ocean is expected to be four times that of hitting the land[2]. Therefore, the study of asteroid hitting the ocean is of great significance.

The impact of asteroids on the ocean is a complex physical process involving many physical dynamic issues and will have many impacts. After investigation and research, we have learned that the tsunami is the most influential factor of an asteroid impact on the ocean[1], and it is also one of the biggest damages to cities.

We divide the whole process into three processes based on the impact of asteroids on the ocean, and establish physical models to analyze and solve the minimum mass of asteroids that cause substantial damage to a city.

Figure1 The three processes of asteroid ocean impact

2 Restatement

This question is to consider the impact of an asteroid hitting the ocean on the city, that is, analyzing the process of the asteroid hitting the ocean, what is the result of the impact, what factors will change or affect the result, and how this result destroys the city. Finally, according to our analysis, combining the criteria for causing substantial damage to the city, calculate the minimum mass required for the asteroid (1,000 kilometers from the coastal city) to cause substantial damage to the city.

3 Assumptions and Notations

3.1 Assumptions

(1) Because causing the tsunami of the same intensity, the iron asteroid needs smaller mass. [6] We assume that irregular asteroids are pure iron balls with uniform mass distribution, which enter the atmosphere at an altitude of 500km from the sea surface.

(2) We ignore the force that causes the trajectory to deflect, such as the Coriolis force, that is, let the flight track angle and heading angle be both 0.

(3) Since the disintegration of asteroids is a complicated process, we assume that after entering the atmosphere, asteroids will not disintegrate, only have the loss of speed and mass.

(4) From (3) we assume that the asteroid does not disintegrate, so we assume that the initial velocity of the asteroid entering the atmosphere is 11.2km/s-12.4km/s.[1]

(5) We assume that the tsunami wavelength is 100km, the shore water depth is 0.3m, the seawater depth 1000km away from the shore is 5000m, and the seawater density is $1.04 \times 10^3 kg/m^3$, acceleration of gravity g is 9.8 m $/s^2$.

3.2 Notations

Variables	Explanations
V	instantaneous velocity of asteroid
h	the current height of the asteroid from the sea
t	the time passed
γ	flight path angle
ψ	flight heading angle
ϕ	current point latitude
ρ_{air}	atmospheric density
r_t	the distance from the asteroid to the center of the earth
ω	angular velocity of the earth's rotation
θ	longitude of current point
C_d	resistance coefficient=1(Dimensionless)
σ	ablation coefficient$\approx 1.0 \times 10^{-7}$ (Bronshten 1983)

ρ_M	density of asteroids
ρ_0	atmospheric density at sea level
$\boldsymbol{H}$	total height of the atmosphere
V_0	the speed at which the asteroid just entered the atmosphere
u	tsunami wave velocity
ω	the Angular frequency
η	vertical displacement from wave surface to static water surface
A	the amplitude of asteroid
ϕ	wave potential function
H	the vertical distance from the bottom of the wave to the top
k	wave number
T	wave period
L	wave length
δ	wave steep
d	water depth

4 Physical Analysis of Model

4.1 Model Establishment and Analysis

4.1.1 Asteroid travels through the atmosphere

In the first place, we analyze the first process, the asteroid travels through the earth's atmosphere to the sea surface. When the asteroid passes through the earth's atmosphere, its speed and mass will be slightly lost. The mass and speed after passing through the atmosphere will be calculated.

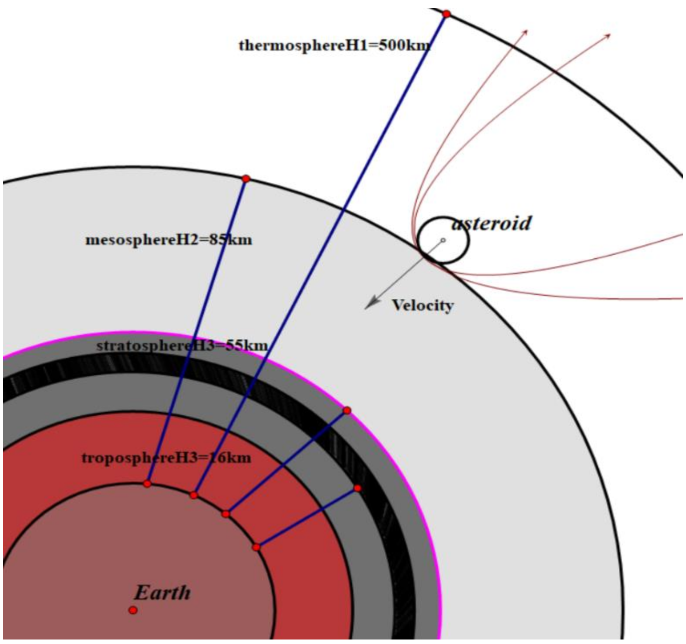

Figure 2 Schematic diagram of asteroid entering the Earth's atmosphere

As shown in Figure 2 is a schematic diagram of the asteroid entering the Earth's atmosphere. Perform dynamic analysis on asteroid, set the mass of asteroid as M and the velocity as V, adopt the spherical earth model and consider the earth's rotation, and only consider the resistance in flight, then the ballistic equations of a single flying body can be written as follows:

$$\left.\begin{aligned}
&\frac{dh}{dt} = V\sin\ \gamma \\
&\frac{d\theta}{dt} = \frac{V\cos\gamma\cos\psi}{r_t\cos\phi} \\
&\frac{d\phi}{dt} = \frac{V\cos\gamma\sin\psi}{r_t} \\
&\frac{dV}{dt} = -C_d \cdot \frac{1}{2M}\rho_{air}V^2 \cdot A - g\sin\ \gamma + \\
&\omega^2 r_t\cos\ \phi(\sin\ \gamma\cos\ \phi - \cos\ \gamma\sin\ \psi\sin\ \phi) \\
&\frac{d\gamma}{dt} = -g\cos\ \gamma + \frac{V^2}{r_t}\cos\ \gamma + \\
&2\omega V\cos\ \psi\cos\ \phi + \\
&\omega^2 r_t\cos\ \phi(\cos\ \gamma\cos\ \phi + \sin\ \gamma\sin\ \psi\sin\ \phi) \\
&d\frac{d\psi}{dt} = -\frac{V^2}{r_t}\cos\ \gamma\cos\ \psi\tan\phi + \\
&2\omega V(\tan\ \gamma\sin\ \psi\cos\ \phi - \sin\ \phi) - \\
&\frac{\omega^2 r_t}{\cos\gamma}\cos\ \psi\sin\ \phi\cos\ \phi
\end{aligned}\right\} \qquad (1)$$

Simplifying the above equations can get the differential equation of the asteroid's velocity change in the atmosphere:

$$\frac{dV}{dt} = -C_d \cdot C\frac{1}{M}\rho_{air}V^2 \cdot A - g\sin\gamma + \omega^2 r_t\cos\ \phi(\sin\ \gamma\cos\ \phi - \cos\ \gamma\sin\ \psi\sin\ \phi) \qquad (2)$$

In this equation, $A = \pi R^2$, R is the instantaneous radius of the asteroid.

γ and ψ are the track angle and heading angle, we assume that the asteroid's flight direction is unbiased, that is γ and ψ are both 0, Equation (2) can be simplified to：

$$\frac{dV}{dt} = -C_d \cdot C\frac{1}{M}\rho_{air}V^2 \cdot A \qquad (3)$$

The mass of the asteroid is： $M = \frac{4}{3}\pi R^3\rho_M$ (4)

Atmospheric density changes with altitude formula：

$$\rho_{air} = \rho_0 e^{-\frac{h}{H}} \tag{5}$$

After ablation, the mass loss can be described by the following formula[3,4,5]:

$$\frac{dM}{dt} = -\frac{1}{2}\rho_{air}V^3A\sigma \tag{6}$$

Simplified by formula (3),(4),(5),(6):

$$\frac{V}{V_0} = \exp\left[-\frac{3}{4}C\left(\frac{\rho_0}{\rho_M}\right)\frac{H}{R}\left(e^{-\frac{h}{H}}\right)\right] \tag{7}$$

In this equation, V is the current speed of the asteroid， h is the current altitude of the asteroid.

Simplified by formula (3) and (6):

$$\frac{dM}{dV} = VM\sigma \tag{8}$$

Based on formula(7),(8),we can calculate the loss of asteroid’s mass and speed.

4.1.2 Asteroid hits the ocean causing a tsunami

An asteroid hitting the ocean is just like hitting on land. Most of the kinetic energy of an asteroid hitting the ocean is involved in the formation of a crater, and this process will expel a lot of sea water, and the asteroid will further contact the mantle. After the asteroid hits the ocean to form a crater, the sea water will rush into the crater, and the sea water rushing into the crater will collide with each other to form waves. Because the crater is deep, surface waves will not be formed, but tsunami waves will be formed.[1]

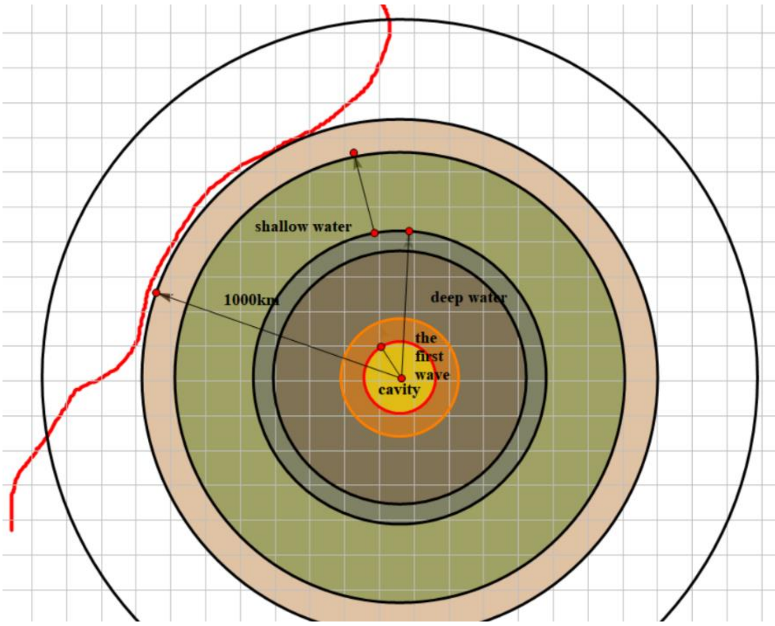

Figure 3 Wave propagation diagram produced by an asteroid hitting the ocean

As shown in the figure 3, the red line is the coastline. After the asteroid hits the sea surface, the waves generated will propagate. Tsunami will spread from deep water to shore.

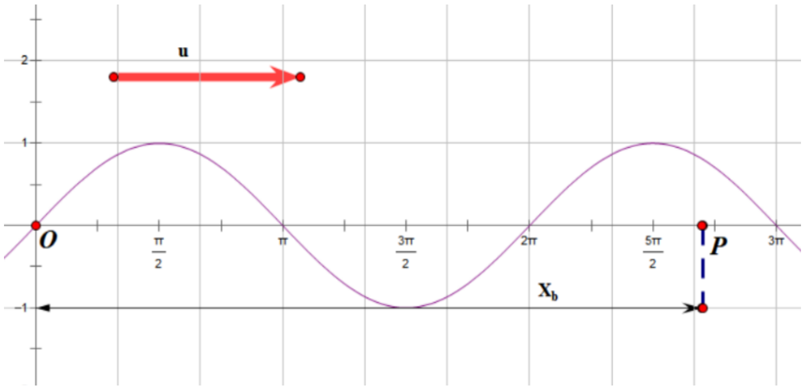

Figure 4 Schematic diagram of wave propagation

Next we conduct physical analysis. As shown in figure 4 ,suppose the point where the asteroid falls on the sea surface is the coordinate origin O, the point pointing to the shore is the positive direction of the x-axis, and the vertical direction (vibration direction of the tsunami wave) is the positive direction of the y-axis. There is a point P in the direction distance O point, the distance between P and O point is x, and the phase of O point is 0 at the initial time. The time required for the vibration to travel from point O to point P is:

$$\Delta t = \frac{x}{u} \tag{9}$$

P point lags behind O point：

$$\Delta\varphi = \omega\frac{x}{u} \tag{10}$$

The vibration equation of water near point O is:

$$y = A\cos(\omega t) \tag{11}$$

The displacement of point P at time t is equal to the displacement of the particle near point O at time $t - \frac{x}{u}$, so the vibration equation of point P is:

$$y(x,t) = A\cos\left[\omega\left(t - \frac{x}{u}\right)\right] \tag{12}$$

Since the point P is chosen arbitrarily, the above equation is the wave function of the plane harmonic.

Next, we derive the energy of the tsunami wave.

We believe that the tsunami wave is ideally not affected by the friction of the seabed. We assume its wave amplitude is A, the total energy density of a wave includes kinetic energy and potential energy. The instantaneous potential energy density can be obtained by the following formula:

$$\rho g\left[\int_{-d}^{\eta} ydy - \int_{-d}^{0} ydy\right] = \rho g\int_{0}^{\eta} ydy = \frac{1}{2}\rho g\eta^2 = \frac{1}{2}\rho gA^2\cos^2(\omega t) \tag{13}$$

Among them, ρ is the density of sea water, and the position of the wave surface is:

$$\eta(x,t) = A\cos(kx - \omega t) \tag{14}$$

Integrate the above formula in one cycle:

$$(1/T)\int_0^T \cos^2(\omega t)dt = 1/2 \tag{15}$$

We have:

$$PE = \frac{1}{4}\rho gA^2 \tag{16}$$

For kinetic energy, the density of the local kinetic energy body is $\rho|\mathbf{u}|^2$, and the integral can be obtained:

$$\rho\int_{-h}^{0} |\mathbf{u}|^2 dz = \rho\int_{-h}^{0} (U^2 + V^2)dz \tag{17}$$

In linear surface gravity waves:

$$\begin{cases} U(x,z,t) = A\omega\frac{\cosh[k(z+h)]}{\sinh(kh)}\cos(kx-\omega t) \\ V(x,z,t) = A\omega\frac{\sinh[k(z+h)]}{\sinh(kh)}\sin(kx-\omega t) \end{cases} \tag{18}$$

Integrate in the vertical direction and within one period:

$$KE = \frac{1}{4}\rho gA^2 \tag{19}$$

Thus the total energy is:

$$E = EK + EP = \frac{1}{2}\rho gA^2 = \frac{1}{8}\rho gH^2 \tag{20}$$

Considering that the wavelength of a tsunami is much greater than the depth of the sea, the energy of a tsunami does not follow the law of energy equalization. So for energy E, there is the following formula:

$$E = \int_{-h}^{\eta}\left(\frac{1}{2}\rho|\mathbf{u}|^2 + \rho gz\right)dz \tag{21}$$

The diameter of the asteroid is:

$$\mathrm{D} = 2\left(\frac{3\mathrm{M}}{4\rho_{\mathrm{M}}\pi}\right)^{\frac{1}{3}} \tag{22}$$

The velocity of the asteroid reaching the sea surface is V , and the energy released by the asteroid at the point of impact is:

$$E_M = \frac{1}{2} M V^2 \tag{23}$$

In the case of an asteroid hitting the ocean, 10-30% of the energy is transferred to the water[6], but most of it will not be transferred to the effectively propagating surface waves. Therefore, we assume that 20% of the asteroid's energy is transferred to the water.

Therefore, the energy of the tsunami wave is:

$$E = 20\% E_M \tag{24}$$

Thus we establish the relationship between the asteroid kinetic energy and the amplitude of the tsunami wave:

$$20\% E_M = \int_{-h}^{\eta} \left(\frac{1}{2}\rho|\mathbf{u}|^2 + \rho g z\right) dz \tag{25}$$

Based on formula (25) we can calculate the mass of asteroid reaching the sea surface.

4.1.3 Tsunami waves propagate to the shore

The third process is that the tsunami wave propagates from the deep sea area to the shallow sea area and the shore. Since the tsunami wave propagates from the deep sea area to the shallow sea area, there is a "shallow water effect". The "shallow water effect" means that the closer the tsunami wave is to the shallow water area, the higher the waves will be. We build a physical model to calculate the amplitude of the tsunami wave reaching the shore. The tsunami propagation process is shown in the figure 5.

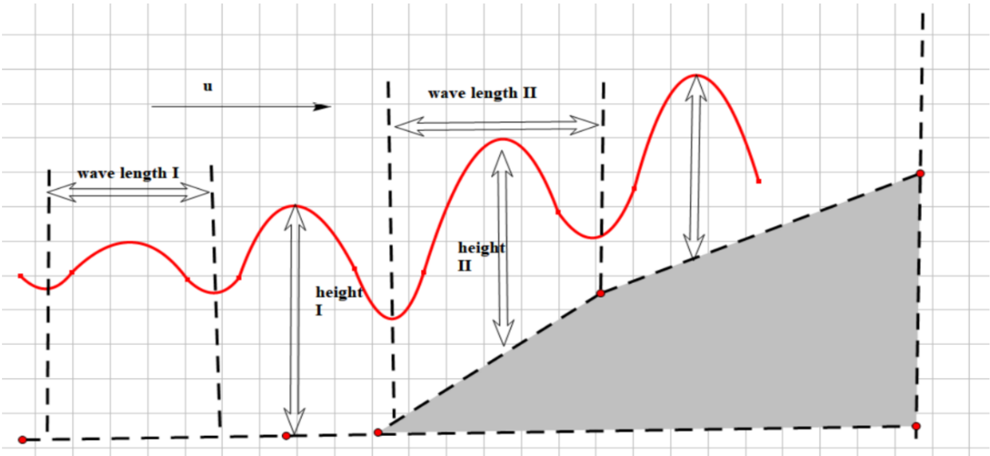

Figure 5 Schematic diagram of tsunami propagation

The second-order Stokes wave theory is widely used in the calculation of the rising height of the wave crest surface[7], so we use the Stokes wave governing equation to establish a model to solve the "shallow water effect" problem of the tsunami near the shore. Assuming that the wave motion is a potential motion, establish a coordinate system that is exactly the same as in 4.1.2, where ϕ is the potential function of the wave, we can write the following Stokes governing equation:

$$\left.\begin{aligned} &\nabla^2\phi = 0 \\ &\frac{\partial\phi}{\partial y} = 0, \\ &\left.\frac{\partial\phi}{\partial t}\right|_{y=\eta} + \frac{1}{2}\left[\left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\phi}{\partial y}\right)^2\right]\Bigg|_{y=\eta} + g\eta = 0 \\ &\frac{\partial\eta}{\partial t} + \frac{\partial\eta}{\partial x}\frac{\partial\phi}{\partial x} - \frac{\partial\phi}{\partial y} = 0, y = \eta \\ &\phi(x,y,t) = \phi(x-ct,y) \end{aligned}\right] \quad (26)$$

In the velocity field:

$$\begin{cases} \boldsymbol{w} = \dfrac{\partial\phi}{\partial z} & （27） \\ \boldsymbol{u} = \dfrac{\partial\phi}{\partial x} & （28） \end{cases}$$

By solving the Stokes governing equation by the perturbation method, the potential function and wave surface of the Stokes second-order solution can be obtained as,

Potential function:

$$\phi = \frac{\pi H}{kT}\frac{\cosh[k(y+d)]}{\sinh(kd)}\sin(kx-\delta t) + \frac{3}{8}\frac{\pi^2 H}{kT}\left(\frac{H}{L}\right)\frac{\cosh[2k(y+d)]}{\sinh^4(kd)}\sin 2(kx-\delta t) \quad （29）$$

Wave surface:

$$\eta = \frac{H}{2}\cos(kx-\delta t) + \frac{\pi H}{8}\left(\frac{H}{L}\right)\frac{\cosh(kd)\cdot[\cos(2kd)+2]}{\sinh^3(kd)}\cos 2(kx-\delta t) \quad （30）$$

Therefore, the formula for calculating the height of the wave crest above the static water surface is:

$$\eta = \frac{H}{2} + \frac{\pi H^2}{2L}\frac{\left(\cosh\frac{2\pi d}{L}\right)\left(\cosh\frac{4\pi d}{L}+2\right)}{4\sin h^3\frac{2\pi d}{L}} \quad (31)$$

Using this formula, we can calculate the amplitude of the tsunami wave reaching the shore.

4.2 Model Solving

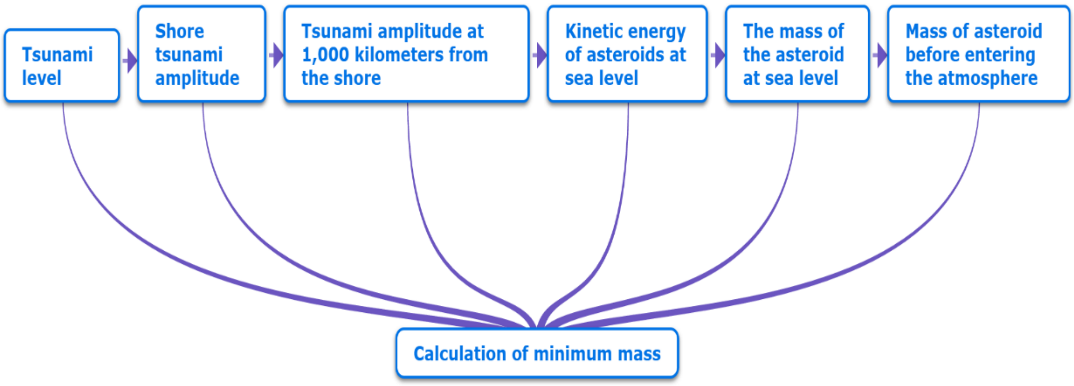

Figure 6 Schematic diagram of minimum mass calculation

According to the above three processes and the physical model we have established, we solve the results. As shown in the figure 6, we solve the problem in reverse.

Tsunami magnitude m	Tsunami height H	Damage
-1	50 cm	None
0	1 m	Very little damage
1	2 m	Coastal and shipping damage
2	4 m ~ 6 m	Damage and lives lost in cer tain land areas
3	10 m ~ 20 m	Considerable damage to the coastal areas
4	30 m	Massive damage to the coastal areas

Figure 7 Watanabe Tsunami Rating Table

First of all, we get the tsunami rating as causing substantial damage to the city is level 3. Internationally, it is said that the size of tsunami is more adopting Watanabe's tsunami grade, as shown in the figure 7, which is used to determine the magnitude of the energy of a certain tsunami.

At this time, the corresponding tsunami amplitude is 10m.

And then the tsunami amplitude at 1000 kilometers can be calculated by formula(31) .

$$\eta = \frac{H}{2} + \frac{\pi H^2}{2L} \frac{\left(\cosh\frac{2\pi d}{L}\right)\left(\cosh\frac{4\pi d}{L}+2\right)}{4\sin h^3\frac{2\pi d}{L}} \quad (31)$$

Thus, the tsunami amplitude at 1000 kilometers is 1.3cm.

From the relationship between the amplitude and the kinetic energy of the asteroid, we can get the mass of the asteroid.

$$20\%E_M = \int_{-h}^{\eta} \left(\frac{1}{2}\rho|\mathbf{u}|^2 + \rho g z\right) dz \quad (25)$$

For a hot asteroid that comes to sea level, about 10% of its total energy is kinetic energy. Based on this, the mass of the asteroid is $1.993 \times 10^{10} kg$, the kinetic energy of asteroid is 1.531×10^{18}J,the speed of asteroid $12.396\ km/s.$

And finally we get the mass of the asteroid before it enters the earth's atmosphere by formula(7),(8). By formula(7),(8), the mass of the asteroid before entering the atmosphere is 2.03 times that of reaching sea level. It is the smallest mass that causes substantial damage to the city.

$$\frac{\mathrm{V}}{\mathrm{V_0}} = \exp\left[-\frac{3}{4}\mathrm{C}\left(\frac{\rho_0}{\rho_M}\right)\frac{\boldsymbol{H}}{\mathrm{R}}\left(\mathrm{e}^{-\frac{\mathrm{h}}{\mathbf{H}}}\right)\right] \quad (7)$$

$$\frac{\mathrm{dM}}{\mathrm{dV}} = \mathrm{VM}\sigma \quad (8)$$

Then the diameter of this iron asteroid is $214.2m$.

The smallest mass asteroid requires that causes substantial damage to the city is $4.046 \times 10^{10} kg.$

5 Conclusion

Based on the physical model we established above, we performed calculations and got some visual conclusions.

We can draw the curve of the asteroid's instantaneous speed versus altitude at different speeds.

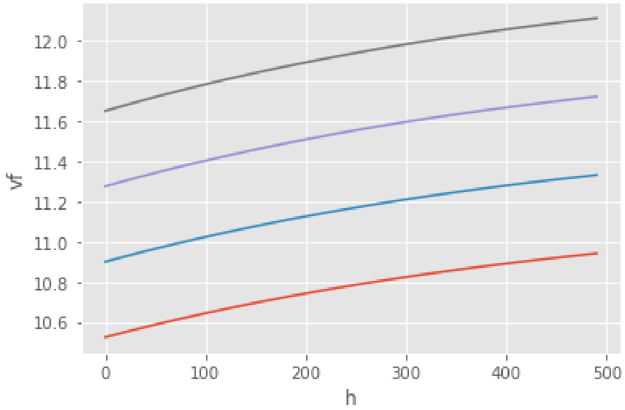

Figure 8 Instantaneous velocity versus altitude

We can get the relationship diagram of the minimum mass corresponding to the asteroids entering the atmosphere at different speeds.

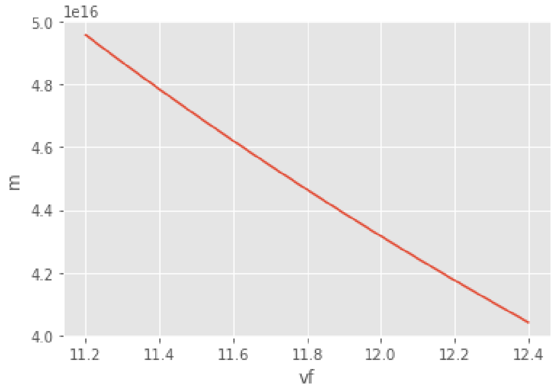

Figure 9 Relationship between initial velocity and minimum mass

In conclusion, when the initial speed is 12.4 km/s, the smallest mass asteroid requires that causes substantial damage to the city is 4.046×10^{10}kg.

6 Strengths and Weaknesses

6.1 Strengths

(1) The model is able to visualize the entire process and calculation results, easy for readers to understand.
(2) The systemic analysis of the complex process is divided into three clear processes to simplify the analysis.
(3) The established model can be closely connected with reality and better reflect reality.
(4) The model is relatively simple and easy to simulate.

6.2 Weaknesses

(1) There are many complex factors in the model, which cannot be fully

considered. For example: The high temperature of the asteroid itself will cause water to evaporate to form a large amount of water vapor, which may cause an explosion, but we did not consider this factor.

(2) In shallow water, the error of the peak height calculated by the Stokes governing equation is slightly larger, and the elliptic cosine wave theory is more adaptable in shallow water.

(3) Some assumptions are ideal, but the reality is difficult to achieve. For example: Coriolis force cannot be ignored in reality, that is, track angle and heading angle will not be 0.

(4) Our model believes that the asteroid will fall vertically after passing through the atmosphere, but it should actually be thrown diagonally downward.

7 Reference

[1] Hills JG, Goda MP. The fragmentation of small asteroids in the atmosphere. *The Astronomical Journal*, 1993, 105 (3): 1114-1144.

[2]ASSESSING ATMOSPHERIC WATER INJECTION FROM OCEANIC IMPACTS. E. Pierazzo, Planetary Science Institute (1700 E. Ft. Lowell, Suite 106, Tucson AZ 85719; betty@psi.edu).

[2] ÖEJ. Physics of Meteor Flight in the Atmosphere. New York: Interscience Publishers Inc., 1958.

[4] Allen GA, Prabhu DK Jr., Saunders DA. Trajectory simulation of meteors assuming mass loss and fragmentation//1st International Workshop on PHA Characterization, Atmospheric Entry and Risk Assessment, NASA Ames Research Center, California, 2015.

[5] Wheeler LF, Register PJ, Mathias DJ. A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus, 2017, 295: 149-169.

[6] Darrel K. Robertsona, Galen R.Near and far-field hazards of asteroid impacts in oceans.Acta Astronautica 156 (2019) 262–277.

[7] Zou Zhili. Coastal Dynamics［M］. Beijing: People's Communications Press, 2010.

Appendix

Python codes

1.Schematic code of instantaneous velocity versus altitude

```
import math
import matplotlib.pyplot as plt
import numpy as np
for v0 in [11.2,11.6,12,12.4]:
    plt.style.use('ggplot')
    h=np.arange(0,500,10)# Generate x-axis coordinates
    vf = []#Define the y-axis coordinate data type
    c=0.5
```

```
        p0=0.001293
        pm=7.8
        R=0.5
        H=500
        for i in h:
            # y-axis coordinate data calculation
            vf.append(v0*math.exp((-3/4)*c*(p0/pm)*(H/R)*math.exp(-i/H)))
        # Bring the x and y axis coordinates into plot() to draw a picture.
        plt.plot(h,vf)
plt.xlabel(u'h')# Display the x-axis noun, u is to change the character code.
plt.ylabel(u'vf')
plt.show()
```

2.Schematic code of instantaneous velocity versus minimum mass

```
import math
import matplotlib.pyplot as plt
import numpy as np
plt.style.use('ggplot')
vf=np.arange(11.2,12.4,0.1)# Generate x-axis coordinates
m=[]# Define the y-axis coordinate data type
E=3.062500127359016e+18
E0=(E/0.2)*0.1
for i in vf:
    m.append((2*E0/i**2)*2.03)# y-axis coordinate data calculation
# Bring the x and y axis coordinates into plot() to draw a picture.
plt.plot(vf,m)
# Display the x-axis noun, u is to change the character code.
plt.xlabel(u'vf')
plt.ylabel(u'm')
plt.show()
```

3.Calculate wave height H

```
import math
n=10
d=0.3
L=100000
delta=0.25+n*(math.pi/(2*L))*(((math.cosh(2*math.pi*d)/L)*(math.cosh((4
*math.pi*d)/L)+2))/((math.sinh(2*math.pi*d/L))**3))
x1=(-
0.5+(delta)**0.5)/(2*(math.pi/(2*L))*(((math.cosh(2*math.pi*d)/L)*(math.cosh((4
*math.pi*d)/L)+2))/(4*(math.sinh(2*math.pi*d/L))**3)))
```

```
x2=(-0.5-(delta)**0.5)/(2*(math.pi/(2*L))*(((math.cosh(2*math.pi*d)/L)*(math.cosh((4*math.pi*d)/L)+2))/(4*(math.sinh(2*math.pi*d/L))**3)))
print(x1)
print(x2)
```

4.Calculate the energy of the wave

```
import math
n=0.012985924244515964
c=(9.8*5000)**0.5
E=0.5*1.04*1000*c**2*(n+5000)+0.5*1000*9.8*(n**2-(5000)**2)**2
print(E)
```

5.Calculate the mass and radius of iron asteroids

```
import math
v0=12.4
c=0.5
p0=0.001293
pm=7.8
R=100
H=500
h=5
vf=v0*math.exp((-3/4)*c*(p0/pm)*(H/R)*math.exp(-h/H))*1000
E=3.062500127359016e+18
E0=(E/0.2)*0.1
m=2*E0/vf**2*2.03
R=(3*m/(4*7.86*1000*math.pi))**(1/3)
print(m)
print(R)
```