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Threat Assessment and Defense Strategies for Asteroid Impacts on Earth: Impact Index Model and its Application

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Abstract:

Near-Earth asteroid impacts have the potential to cause catastrophic damage, making it imperative to develop robust defense strategies to mitigate these risks. Understanding Near-Earth asteroid impact dynamics and potential effects becomes crucial for global disaster preparedness and response efforts. This study presents an impact index model designed to guide preliminary defense strategies against near-earth asteroid impacts, which pose significant threats to humanity. The model is informed by numerical simulations and engineering calculations, providing a high-fidelity analysis suitable for fine-grained assessment of impact effects. This paper adopts principal component analysis and factor analysis to optimize the impact index model, catering to asteroids with incomplete observational data. The research investigates the effects of asteroid disintegration, explosion, and tsunami, enhancing the formulation of defense policies and deepening the understanding of impact effects. The study's results indicate that the proposed model can effectively assist in preemptive strategic planning to mitigate potential disaster losses.

Keywords: Aerospace Engineering, Impact index model, Numerical simulation, Defense strategies, Factor Analysis

1. Introduction

The impact of a near-Earth asteroid on the Earth has been recognized as one of the potential threats to human survival and development. It is recognized that the impact of a 10-km-diameter asteroid on the Chicxulub region of Mexico 65 million years ago led to the global extinction of all species, including the dinosaurs, which is known as the K-T event [1]. On June 30, 1908, an asteroid impact occurred in Tunguska, Siberia, Russia, releasing about 10 million tons of TNT-equivalent energy and causing widespread damage to trees on the ground [2]. On February 15, 2013, a meteor measuring 20 m exploded and disintegrated in the sky, releasing about 500,000 tons of TNT-equivalent energy and causing significant damage in Chelyabinsk, Russia. The energy released was about 500,000 tons of TNT equivalent, causing great damage [3].

When an asteroid impacts the Earth, it triggers a series of physicochemical and mechanical processes, and these reactions lead to many types of entry and impact effects and cause disasters [4]. After the asteroid airburst, the shock wave propagates to the ground, causing overpressure damage to the ground; the thermal radiation generated by the explosion is transmitted to the ground, causing thermal radiation damage. After the asteroid penetrates the atmosphere, the direct impact on the land produces impact craters, the direct impact on the ocean may cause tsunamis, the direct impact may also throw part of the material into the air, and the splashback debris cloud produced by its impact may cause global climate change.

Numerical simulations and engineering calculations are used to analyze the effects of asteroid entry and impact. Numerical simulations are high-fidelity, time-consuming, and suitable for detailed analysis of specific impact events or hazard types. Boslough and Robertson used the numerical method of impact dynamics to study the asteroid entry into the atmosphere, airborne explosions, and tsunamis triggered by impacts on the ocean [5, 6]. Their results show that these extreme events of asteroids can have serious impacts on the Earth, and in particular, the tsunamis that may be triggered upon impact with the oceans pose a serious threat to coastal areas.

Aftosmis and Collins investigated the propagation process of blast waves generated by airborne explosions based on a numerical method of compressible aerodynamics [7, 8]. Their results show that the propagation and impact range of the blast wave are closely related to the height and energy of the explosion. Compared with the traditional static point explosion model, their model can more accurately predict the impact of the explosion wave on the ground, especially when the explosion energy is large, the accuracy of the model is more significant.

Johnston studied the thermal radiation generated by the entry process by using high-temperature gas dynamics numerical simulations coupled with high-temperature ablation flow fields and radiation calculations [9]. His results revealed the potential impact on the ground of the thermal radiation generated during the asteroid entry process into the atmosphere, which could lead to fires and other heat-related disasters.

Zhang and Zhao initially investigated the impact crater formation process by utilizing impact dynamics numerical software [10, 11]. Their results show that the formation of impact craters not only depends on the size and impact velocity of the asteroid, but is also affected by the geological conditions on the ground.

Li carried out numerical simulations of airborne explosions and their impact on the sea surface [12]. His preliminary study showed that both airborne explosions and sea impacts could trigger catastrophic consequences including, but not limited to, tsunamis and extensive ground damage.

Due to the severity of the hazard of asteroid impacts and the unpredictability of disasters caused by asteroid impacts, this paper proposes an impact index to provide a guide for countries to pre-process their defense against observed asteroid impacts to reduce the disaster damage caused by the event.

This paper calculates and analyzes historical data, using principal component analysis and factor analysis, and further optimizes the method. The methodology is optimized so that the maximum fit impact index can be assigned to asteroids that do not have part of their data measured in time, to assist in the formulation of defense policies, and to improve the understanding of the effects of asteroid entry and impacts.

2. Background to the Issue

Asteroid impacts on Earth pose a potential threat to human survival and development. In the past two decades, planetary defense has become a popular research field, and the guarantee of China's security has a significant demand for planetary defense. In the face of asteroid impacts, it is an urgent task for human beings to accurately predict the hazards brought by asteroids and give an efficient, safe, and economical defense. This paper introduces cases of asteroid impact hazards, and quantitatively describes the possible hazards of different asteroids with impact indices from the perspective of the principle of asteroid impact hazards, to provide guidance to each country in dealing with the defense against observed asteroid impacts, and to reduce the disaster losses caused by the events in question. Using principal component analysis and factor analysis, an analytical model of the factors influencing the impact index is presented. Fig. 1 shows the global distribution of impact events received.

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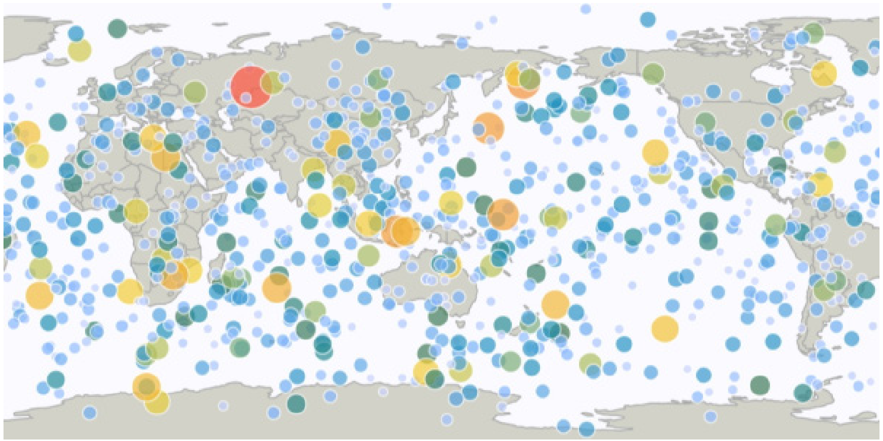

Fig. 1 Global distribution map of fireball impact events [13].

3 Methodologies

3.1 Data Processing and Analysis

First, the data that have been collected are normalized and pre-processed so that each variable has a mean of 0 and a standard deviation of 1. There are the following equations:

$$Z_{ij} = \frac{\left(X_{ij} - \bar{X}_j\right)}{S_j} \tag{1}$$

Where Z_{ij} is the normalized value, X_{ij} is the original data, $\bar{X}_j$ is the mean of the JTH variable and S_j is the standard deviation of the JTH variable.

Calculate the correlation coefficient matrix:

The normalized data can be used to calculate the correlation matrix R which represents the linear relationship between the variables. The elements of the correlation coefficient matrix r_{ij} can be calculated using the following formula:

$$r_{ij} = \frac{\sum_{k-1}^{n}\left(Z_{ij} - \bar{Z}_i\right)\left(Z_{jk} - \bar{Z}_j\right)}{\sqrt{\sum_{k-1}^{n}\left(Z_{ik} - \bar{Z}_i\right)^2}\sqrt{\sum_{k-1}^{n}\left(Z_{ik} - \bar{Z}_j\right)^2}} \tag{2}$$

Using factor analysis, factors with a contribution rate of 85% or more were selected as variable factors for the linear fit, and the contribution rate of six variables to the impact energy of the fireball was used as a reference for the effect on the impact index; the six variable factors were: altitude at the time of discovery, total velocity, velocity on the x-component, velocity on the y-component, velocity on the z-component, and total radiant energy.

3.2 Model

Linear regression model for impact index E_t

The impact index E_t is a linear model where E_t is the dependent variable, x factors are independent variables, β_0 is the intercept term, β_1 is the slope (regression coefficient) and ? is the error term. The linear regression model can be expressed as follows:

$$E_t = \beta_0 + \beta_1 x + \epsilon \tag{3}$$

Ordinary least square (OLS)

To estimate the model parameters β_0 and β_1, the maximum square method is used, which minimizes the sum of squares of the error terms, which correspond to each observation only.

The error term e_i represents the difference between the predicted and actual values for the i th observation.

$$e_i = E_{t_i} - \widehat{E_{t_i}} \tag{4}$$

$$e_i = E_t - \left(\beta_0 + \beta_1 x_i\right) \tag{5}$$

The sum of error squares SSE is defined as:

$$SSE = \sum_{i=1}^{n} e_i^2 \tag{6}$$

Solving for regression coefficients

To minimize SSE, it is necessary to take the partial derivatives of β_0 and β_1 and set them to zero. This will produce two regular equations, and by solving them, estimates of β_0 and β_1 can be obtained.

Partial derivatives with respect to β_0:

$$\frac{\partial SSE}{\partial \beta_0} = \sum_{i=1}^{n} 2(E_{t_i} - (\beta_0 + \beta_1 x_i))(-1) \tag{7}$$

partial derivatives with respect to β_1:

$$\frac{\partial SSE}{\partial \beta_1} = \sum_{i=1}^{n} 2(E_{t_i} - (\beta_0 + \beta_1 x_i))(-x_i)\#(8) \qquad (8)$$

4. Result

Separate quadratic polynomial fits the relationship between the six selected independent factors and the impact energy that directly affects the impact index E_t were performed using Matlab and plotted as linear fits with scatter plots (e.g., Figures 2-7).

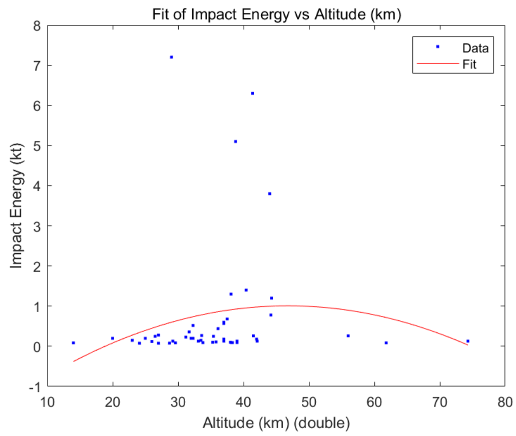

Fig. 2 Altitude (km) vs. Calculated Total Impact Energy (kt) (Photo/Picture credit: Original).

The relationship between altitude (in kilometres) and the calculated total impact energy (in kilotons) is demonstrated through scatter Fig. 2. The observed data points show a slightly increasing trend, which indicates that as the altitude increases, the total impact energy shows a corresponding increase. Through linear regression analysis, the slope of the linear fit line was found to be significantly positive with a specific value of approximately 0.002, which indicates that for every 1 km increase in altitude, the total impact energy increases by an average of 0.002 kilotons. In addition, the value of the correlation coefficient $R^2$was 0.42, which indicates that, although there is some linear correlation, altitude explains only 42 percent of the variation in total impact energy.

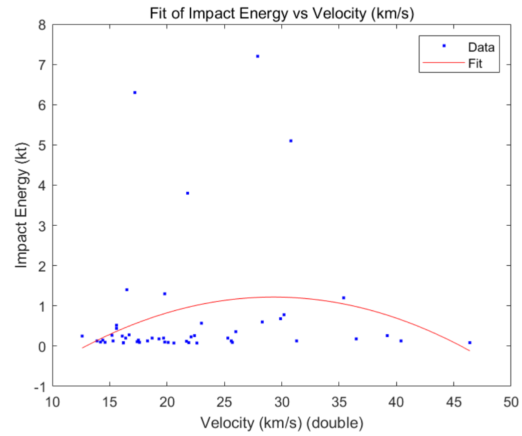

Fig. 3 Velocity (km/s) vs. calculated total impact energy (kt) (Photo/Picture credit: Original).

The potential relationship between velocity (in kilometers per second) and the calculated total impact energy (in kilotons) was analysed using scatter Fig. 3. The observed data points are roughly distributed along a nearly horizontal straight line, which implies that an increase in velocity does not have a significant effect on the total impact energy. A linear regression analysis revealed that the slope of the linear fit line varied by a small amount, suggesting that the change in velocity had a negligible effect on the total impact energy. In addition, the low value of the correlation coefficient R^2 suggests a small contribution of velocity to the total impact energy.

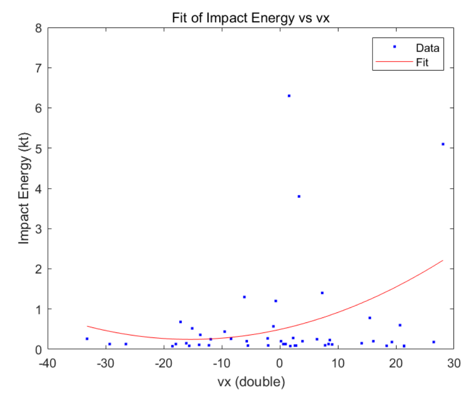

Fig. 4 v_x (km/s) vs. calculated total impact energy (kt) (Photo/Picture credit: Original).

The potential relationship between the velocity component v_x (in kilometrsr per second) and the calculated total impact energy (in kilotons) was analysed by means ingscatter Fig. 4. The observed data points were spread out on the graph and did not show a clear upward or downward trend, suggesting that the relationship between v_x and the total impact energy was not significant. Further analysed through linear regression, the line of linear fit was found

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to be almost horizontal with a slope close to zero, which further confirms that the effect of v_x on total shock energy is not significant. In addition, the value of the correlation coefficient $R^2$is very low, indicating that the relationship is very weak, i.e., changes in v_x have very limited predictive power for total shock energy.

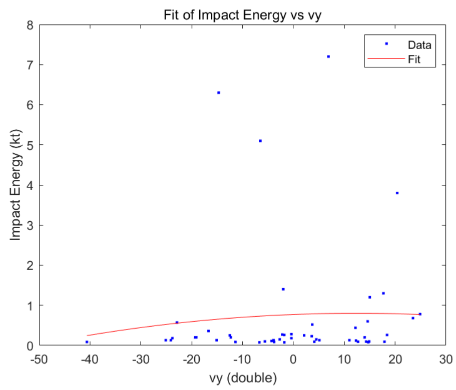

Fig. 5 v_y (km/s) vs. Calculated Total Impact Energy (kt) (Photo/Picture credit: Original).

The relationship between the velocity component v_y (in kilometres per second) and the calculated total impact energy (in kilotons) was analysed by means of scatter Fig. 5. The observed data points show a slight negative correlation trend and the slope of the linear fit line is negative, which implies that the total impact energy shows a slight decreasing trend as v_y increases. However, the absolute value of the slope is very small, suggesting that v_y has a very limited effect on the total shock energy. In addition, the relatively low value of the correlation coefficient R^2 further confirms that v_y can only explain a small fraction of the total shock energy variance. This finding suggests that although v_y plays a role in the impact process, its contribution to the total impact energy is relatively small.

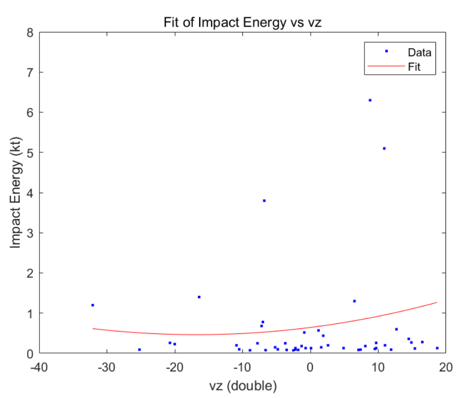

Fig. 6 v_z (km/s) vs. Calculated Total Impact Energy (kt) (Photo/Picture credit: Original).

The potential link between the vertical velocity component v_z (in kilometers per second) and the calculated total impact energy (in kilotons) was meticulously analyzed by means of scatter Fig. 6. The results show that the data points are scattered throughout the coordinate system and lack a clear tendency to cluster, suggesting that there is no significant correlation between v_z and the total impact energy. Further linear regression analysis revealed that the line of linear fit was nearly horizontal with a slope close to zero, a finding that further confirms the negligible effect of x on total shock energy. In addition, this is further confirmed by the extremely low level of the correlation coefficient R^2value, indicating that v_z explains only a very small portion of the variation in total shock energy.

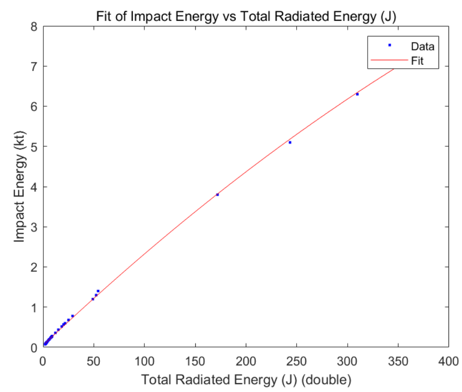

Fig. 7 Total Radiated Energy (J) vs. Calculated Total Impact Energy (kt) (Photo/ Picture credit: Original).

The relationship between the total radiant energy in joules and the calculated total shock energy in kilotons was analyzed in detail through scatter Fig. 7. The results show that the data points exhibit a strong positive correlation trend, which indicates that as the total radiant energy increases, the total shock energy also increases significantly. This is further confirmed by the linear regression analysis, where the slope of the fitted line is positive and relatively large, indicating a significant positive correlation between total radiant energy and total shock energy. In addition, the correlation coefficient R^2 value is very high, indicating that the total radiant energy explains a large portion of the variance in the total shock energy, illustrating the strong linear relationship between the two.

The fitted curves were further analyzed for the relationship between the first six variable factors on impact energy, and the Estimate, SE, tStat, and pValue were calculated for each of them.

Table 1. Results of the regression model

	Estimated value	Standard error	T-statistic	P-value
Estimated coefficient	0.017887000	0.038819	0.46077	0.647340
x_1	0.00216320	0.0013522	1.59970	0.117150
x_2	-0.00034367	0.0017203	-0.19977	0.842630
x_3	0.00046851	0.00076109	0.61557	0.541500
x_4	0.00148110	0.00071881	2.06050	0.045579
x_5	-0.00119030	0.00092666	-1.2845	0.206050
x_6	0.02029400	0.00014158	143.33	38997e-58

Based on the data obtained from the calculations in Table 1, it is shown that x_4 and x_6 have a significant effect on the impact index E_t.

The guiding equation for the impact index E_t is:

$$E_t = 0.0022x_1 - 0.0003x_2 + 0.0005x_3 + 0.0015x_4 - 0.0012x_5 + 0.0203x_6 + 0.0179 \quad (9)$$

where x_1 to x_6 are in order, the altitude at the time of discovery, the total velocity, the velocity on the x-component, the velocity on the y-component, the velocity on the z-component, and the total radiant energy.

5. Solutions for Star Impact Defense

Based on the prior analysis, the values found by substituting the data from the recorded impact events were concentrated between 0 and 25, and the following three defense strategies were developed in conjunction with the data analysis.

5.1 Low Impact Response Program

When the value of E_t is in the interval 0~0.2

The most important measure is to thoroughly study the orbits of known near-Earth asteroids and Earth-skimming comets, to accurately grasp the evolution of the orbit, and to systematically monitor the inevitably very limited hazardous targets [14]. The main scientific issues include: (1) how to accurately predict asteroid orbits; (2) constructing kinetic models of asteroid orbital evolution; and (3) asteroid orbital resonance and asteroid structural stability [15].

5.2 Medium Impact Response Program

When the value of E_t is in the interval 0.2~0.25.

Enhancement of the monitoring system: establish and maintain a global monitoring network for continuous observation and tracking of near-Earth asteroids.

Data sharing and analysis: Ensure that all observational data can be shared in real-time and analyzed in depth for timely detection of potential threats.

Public education: Raise public awareness of the risk of asteroid impacts and increase public awareness of the response through education and media outreach.

International cooperation: Strengthen international cooperation to jointly develop monitoring technologies and response strategies.

5.3 High Impact Response Programs

When the value of E_t is in the interval 0.25~∞.

According to the duration of action and the size of the asteroid, there are a variety of asteroid in-orbit disposal methods, there are two categories: instantaneous action means and long-term action means [16].

For asteroids with short warning time, instantaneous means of action are used to deal with the large size of the use of nuclear explosions to destroy or change the orbit, and the small size of the use of kinetic impact [16]. For asteroids with long warning times, kinetic impacts can be used to produce instantaneous velocity changes to alter the asteroid’s orbit, or prolonged contact or non-contact effects can be applied to produce small velocity increments that can be extrapolated over time to produce large orbital deflections [15]. Methods of altering asteroids using long-term effects include advective push-off, ion beam push-off, mass drive, gravitational pull, solar pressure, and laser ablation [16]. These methods generally require warning times of years or even decades and are suitable for defense against asteroids with sufficiently long warning times [16].

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6. Conclusion

This paper provides an in-depth discussion of the threat posed by near-Earth asteroid impacts on the Earth and proposes a scientific assessment system, the impact index model, to quantify the hazards that may be caused by asteroid impacts. From the impact index formula, it can be found that the altitude, velocity and velocity component, and energy at the time of discovering the asteroid are the main influencing factors in determining the impact index, compared with the negligible influence of the asteroid's attributes such as its type, material, and shape on the impact index. Through the analysis of historical data and the application of numerical simulation methods, not only the physical processes and potential impacts of asteroid impacts are revealed, but also a comprehensive assessment framework is established to guide countries to take effective defense measures in the face of asteroid threats.

The article first reviews several major asteroid impacts in history, such as the K-T, Tunguska, and Chelyabinsk events, and emphasizes the potential destructive power of asteroid impacts on the Earth's ecology and human society. Then it details the process of constructing the impact index model, including data normalization, calculation of the correlation coefficient matrix, factor analysis, and linear regression modeling. The application of these methods enables us to filter out the key variables from numerous impact factors and construct an impact index model with high explanatory power.

In addition, this paper proposes defense strategies for different values of the impact index, ranging from monitoring and education for low impacts to technological interventions for medium impacts, to emergency response measures for high impacts, providing a comprehensive set of solutions for global planetary defense. These strategies are proposed not only based on scientific analysis, but also considering the feasibility of practical operation and the necessity of international cooperation.

In conclusion, the research in this paper not only improves our understanding of the asteroid impact threat but also provides practical tools and strategies for planetary defense. With the continuous progress of science and technology and the deepening of international cooperation, it have reason to believe that human beings will be able to respond more effectively to the challenges of the universe and protect our planet from the threat of asteroid impacts.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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