RE-ENTRY RISK ASSESSMENT FOR CATASTROPHIC EVENTS

Cristina de Persis[(1)], Csaba Jeger[(2)], Stijn Lemmens[(3)], Guillermo Ortega[(4)]

(1) ATG for European Space Agency, The Netherlands, Email: Cristina.De.Persis@ext.esa.int
(2) HE SPACE for European Space Agency, The Netherlands, Email: Csaba.Jeger@ext.esa.int
(3) European Space Agency, Germany, Email: Stijn.Lemmens@esa.int
(4) European Space Agency, The Netherlands, Email: Guillermo.Ortega@esa.int

ABSTRACT

This paper focuses on a detailed mathematical model that is able to calculate the break up and fragmentation process occurring during catastrophic events. Catastrophic events are defined as events that produce a large number of casualty and fatality rates. The work reported in this paper shows different scenarios in which an asteroid hits the Earth producing a catastrophic event.

The paper shows that the mathematical model of the break up and fragmentation process has been programmed in a software tool and the corresponding casualty and fatality curves are computed. The complete model takes into account the impact of the asteroid and the subsequent destruction of life and property after the impact.

The model divides the destruction process in consecutive segments starting from the instant of the impact and allows the forecast of the progression of casualties and fatalities until reaching the highest level of damage (which could culminate in a massive extinction event). This mathematical model has been validated with previous recorded catastrophes and represents a positive step in the protection of civilians and their habitats, dividing the population into the sheltered and un- sheltered.

The model uses an accurate world population data base, the latest model of the Earth's atmosphere, and high accuracy re-entry trajectories for the threatening asteroid. The paper details a parametric study based on the size and composition of the asteroid, the flight path velocity, and the flight path angle. All this data is combined to generate results that can be used as input for civilian protection national and international programs.

1. CATASTROPHIC EVENTS

The purpose of the study was to conduct a parametric analysis to calculate fatality curves as a function of the size of an asteroid impact with Earth, its inner composition, its speed, its flight path angle at Earth entry, and its primary impact location on our planet. This massive amount of data shows revealing conclusions that will be shown in this paper.

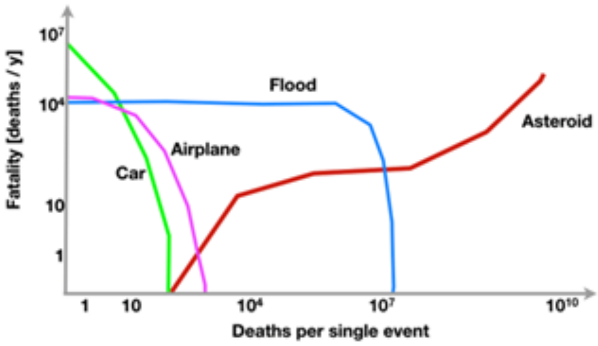

Figure 1. Deaths versus fatality curve

The paper is complemented by a presentation handout (available on demand) that contains the display of a realistic set of videos made from the simulations of one of the most damaging impacts of the asteroid simulation sets. The videos show the propagation of the extinction wave for the most dramatic case.

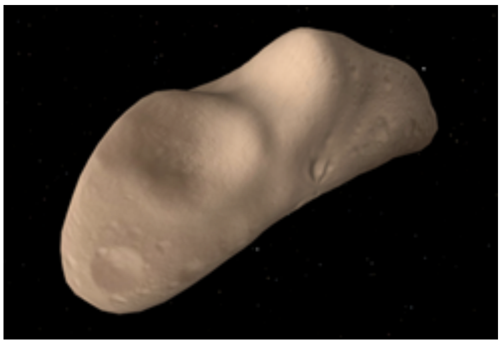

Figure 2 Polyhedron model of the asteroid "Eros"

It must be pointed out that no registry of anybody ever been killed by an asteroid impact has been made till date. Therefore, this research acknowledges that the threat of the case of the asteroid or comet hitting Earth is small in comparison with other catastrophes. Figure 1 shows the death per single event versus the corresponding fatality expressed in deaths per year. For example, the graph shows that the yearly probability to be killed in a car accident is higher that the probability to die in an airplane accident or in a flood. And much

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higher than the probability to die due to an asteroid impact with Earth. However, it is evident that a medium size asteroid impact with Earth is more lethal than anything Earth or humans are capable of producing on the scale of massive destruction. The current study also provides awareness of the Earth's fragility and establishes grounds for studying the risk management to population in the following terms: quantification of the magnitude of the risk, the identification of risk contributions, the study of damage to life and properties, and open discussion about the uncertainties in the mathematical model.

The following definitions are used in this paper:

Earth catastrophic event: more than 10.000 people killed at the same time.

Property damage: damage to fixed and non-fixed property owned by a person or group of persons.

Casualty: a person suffering a serious injury as the result of a catastrophic event.

Fatality: a person suffering death as the result of an accident associated with a catastrophic event.

Maximum Probable Loss (MPL): the greatest Euro amount of loss for bodily injury or property damage that is reasonably expected to result from a catastrophic event.

2. ASTEROID THREAT

The Table 1shows a catalogue of asteroid threats as a function of the diameter of an asteroid impacting the Earth. The damages go from local destruction to the total planetary collapse. The minimum impact velocity on Earth is 11 km/s. The typical impact velocities are more than 15 km/s for asteroids and more than 50 km/s for comets. The maximum Earth impact velocity for objects orbiting the sun is 72 km/s.

To allow a comparison, the Hiroshima and Nagasaki atomic bombs were 20 Kilotons (KT) of energy. The biggest ever recorded Earthquake magnitude has been 9.5. The K-T boundary extinction (Cretaceous–Tertiary extinction event) energy was about 1E+7 MT. And the energy to boil all Earth oceans is about 2E+9 MT. Figure 2 shows two graphs of the known asteroids versus their know diameters and their age. Bigger asteroids are far away and are older that smaller nearer objects in average.

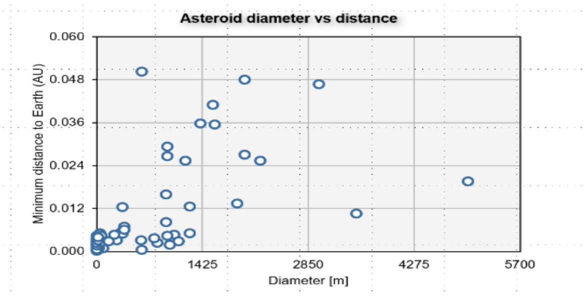

Figure 3 Asteroids versus diameter

3. SCENARIOS

The simulation work reported in this paper has been segmented into phases as follows:

Phase 1: represents the travel in space of the asteroid. The asteroid travels in space with the simulation starting at around GEO altitude (i.e. 42000 km approximately).

Phase 2: is the phase when the asteroid is entering the Earth atmosphere: the asteroid enters Earth atmosphere at 120 km.

Phase 3: is the impact with Earth at the impact point and flight of ejecta around.

Phase 4: represents the shock wave and how it propagates on Earth from the impact point and in the direction of the azimuth foreseen.

Diameter [Km]	Kinetic energy at impact [MT]	Recurrence interval time of the same impact again [y]	Crater diameter [Km]	Crater depth [Km]	Earthquake magnitude [Richter]	Severity
0.01	0.06	6.38	0.3	0.4	3.8	Local destruction
0.1	75.16	1,583.60	1.9	0.6	5.9	Local catastrophe
1	7.52E+04	346,454.27	11.4	1.0	7.9	Regional catastrophe
5	9.39E+06	1.50E+07	39.9	1.5	9.3	Global catastrophe
10	7.52E+07	7.58E+07	68.5	1.8	9.9	Massive extinction
100	7.52E+10	1.66E+10	412.9	3.0	11.9	Planetary collapse

Table 1 Asteroid threat catalogues as a function of the diameter [1]

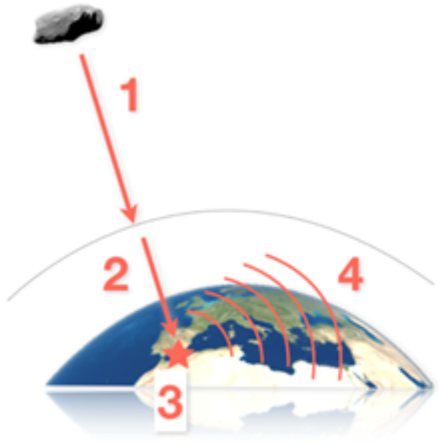

Figure 4 Simulation scenario segmented in phases

Figure 4shows a schematic view of the simulation segmented into 4 phases. To these phases the study also adds a phase, called phase 4+1, taking into account the aftermath long-term effects after the shock wave propagation. Figure 5 also shows the targeted impacts with their corresponding asteroid diameter sizes. The impact points have been chosen as to reflect dispersed areas of the Earth. The sizes of the asteroid range from 10 meters to 100 Kilometers. The impacts points are Amanu, Houston, Verona, Granada, and Tokyo.

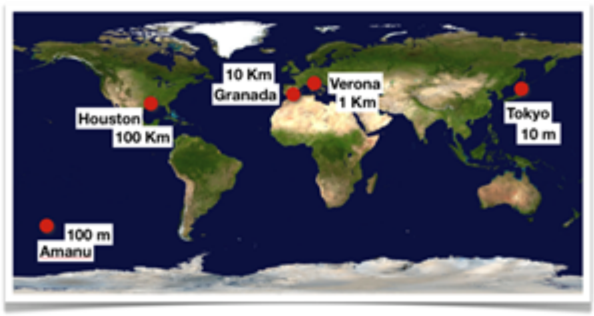

Figure 5 Targeted impact points with asteroid diameters

The present asteroid scenario study takes into account the ATV re-entry experience by re-using techniques and technologies from the former work in the ESA project.

4. USING ASTOS

The software tool used in the analysis and simulations reported in this paper is ASTOS.

Trajectory risk analysis tools are starting to become important assets to address the human casualty risk from any portions of the spacecraft or orbital stages that may survive atmospheric re-entry. These tools shall not only include the calculation of casualty area but also the casualty and fatality probabilities.

ASTOS software (see Figure 6 and Figure 7) is a simulation and optimization environment to compute optimal trajectories for a variety of complex multi-phase optimal control problems. It consists of fast and powerful optimization programs, PROMIS, CAMTOS, SOCS and TROPIC, that handle large and highly discretized problems, a user interface with multiple plot capability, and GISMO, an integrated graphical iteration monitor to review the optimization process and plot the state and control histories at intermediate steps during the optimization.

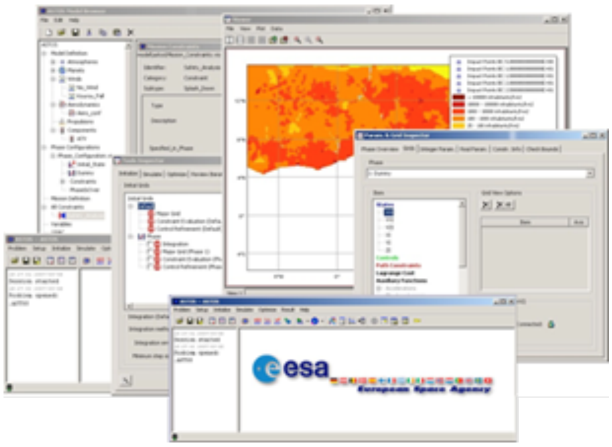

Figure 6 ASTOS screenshots

Since 1995, ASTOS is being developed in collaboration with the Technical Directorate of the European Space Agency at ESTEC. Since 2005, three modules were added inside ASTOS: DARS (Debris Analysis for Re-entering Spacecraft) that calculates the vehicle re-entry considering break-up and demise [2], and DIA (Debris Impact Analysis) [3]that calculates the impact based on ballistic coefficients. On top the risk probabilities of casualties and fatalities can be calculated with RAM (Risk Analysis Module).

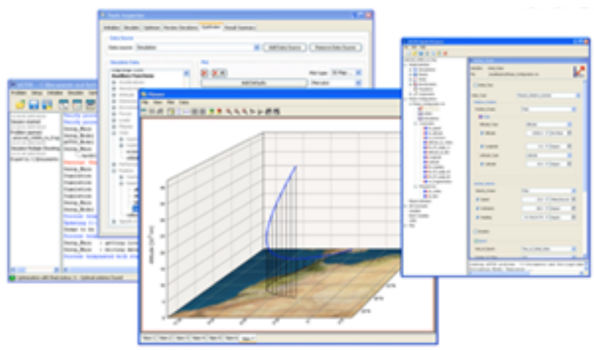

Figure 7 ASTOS screenshots

DARS, as a deterministic tool, considers not only a vehicle break-up, but also melting of the fragments, taking diverse materials and shapes into account. DIA is based on ballistic coefficients and allows safety analysis in combination with additional impulses during the break-up already in early project phases. Both, DIA and DARS can be combined with stochastic methods for extensive calculations of variations. RAM calculates the casualty cross-section (Ac) of a re-entry object.

ASTOS can generate plots in 2D and 3D. The inputs to this process are the scenario, vehicle, orbital dynamics, and the outputs are trajectories, foot-prints, dispersion ellipsoids, reports, etc. ASTOS uses the population data from the Gridded Population of the World Version 4 (GPWv4). GPWv4 depicts the distribution of human population across the globe. It is the most detailed version of GPW to date with more than three times the amount of data as version 3, and includes population estimates to 2021.

Asteroid features							Impact consequences									
Material density [kg/m3]	Diameter [Km]	Surface [m2]	Volume [m3]	Mass [Kg]	Flight path velocity [Km/s]	Flight path angle [deg]	Kinetic energy at impact [J]	Kinetic energy at impact [MT]	Recurrence interval time of the same impact again [y]	Crater diameter [Km]	Crater depth [Km]	Earthquake magnitude [Richter]	Initial ground speed of ejecta [m/s]	Ejecta time to reach ground [s]	Maximum height of ejecta [Km]	Extinction
3000	0,01	7,9E+01	2.094,3	15282	10	45	7E+13	0	2,16	0,2	1	3,4	3.924,6	0,1	0,00	No
3000	0,1	7,9E+03	2,1E+06	3E+9	10	45	8E+16	19	537,08	1,4	1	5,4	4.254,5	0,9	0,00	No
3000	10	7,9E+07	2,1E+12	3E+15	10	45	8E+22	1.91E+7	25.706.273,22	50,5	2	9,5	4.254,5	86,8	36,94	YES
3000	100	7,9E+09	2,1E+15	3E+18	10	45	8E+25	19138755 981	5.623.919.805,50	304,4	3	11,5	4.254,5	868,3	3.694,07	YES
3000	0,01	7,9E+01	2.094,3	15282	20	45	3E+14	0	6,38	0,3	1	3,8	7.849,1	0,2	0,00	No
3000	0,1	7,9E+03	2,1E+06	3E+9	20	45	3E+17	72	1.583,60	1,9	1	5,9	8.509,0	1,7	0,01	No
3000	10	7,9E+07	2,1E+12	3E+15	20	45	3E+23	71770335	75.795.934,61	68,5	2	9,9	8.509,0	173,7	147,76	YES
3000	100	7,9E+09	2,1E+15	3E+18	20	45	3E+26	71770335	16.582.343.699,51	412,9	3	11,9	8.509,0	1.736,5	14.776,26	YES
3000	0,01	7,9E+01	2.094,3	15282	30	45	6E+14	0	12,01	0,4	1	4,0	11.773, 7	0,3	0,00	No
3000	0,1	7,9E+03	2,1E+06	3E+9	30	45	7E+17	167	2.980,91	2,3	1	6,1	12.763, 6	2,6	0,03	No
3000	10	7,9E+07	2,1E+12	3E+15	30	45	7E+23	16746411 5	142.675.129,88	81,9	2	10,1	12.763, 6	260,5	332,47	YES
3000	100	7,9E+09	2,1E+15	3E+18	30	45	7E+26	16746411 4833	31.213.917.385,17	493,5	3	12,1	12.763, 6	2.604,8	33.246,59	YES

Table 2 Round of performed simulations and their main parameters.

5. PHASE 1: INTERPLANETARY TRIP

The phase 1 of the simulation study represents the travel in space of the asteroid. The simulation starts at around GEO altitude (i.e. 42000 km approximately).

The asteroid flight speed at that altitude is between 20 to 30 km/s. The simulation date chosen is December 21st, 2012.

Figure 8shows a screenshot of the video made from the asteroid trajectory for phase 1. The average density of the simulated asteroid ranges from 3000 to 4000 kg/m3. Its composition is a mixture of olivine and pyroxene with the following ingredients and their corresponding percentages: Mg (10.98%), Fe (12.33%), Si (35.67%), O (14.05%), Ca (19.54%), Al (4.71%), Na (0.81%), K (0.14%), Ti (0.58%), Mn (0.23 %), H (0.96%).

Figure 8 Screenshot of video of the asteroid flight for phase 1

7. PHASE 2: ENTERING THE ATMOSPHERE

This phase simulates when the asteroid is entering the Earth atmosphere at 120 km altitude. As shown in Table 2, it has been carried out an entry parametric analysis of several diameter sizes asteroids, several flight path angles and flight path azimuths.

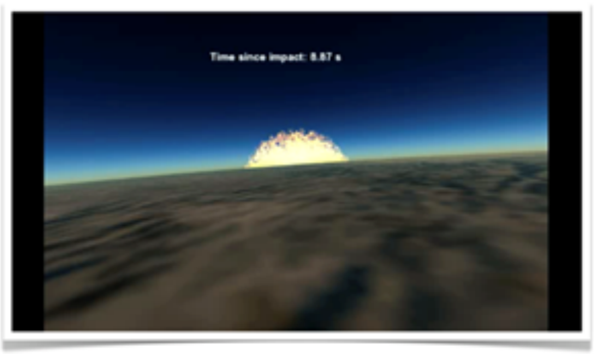

Figure 9 Screenshot of the videos made for the impact with Earth without fragmentation

Based on the performed parametric analysis, the mathematical model used is able to calculate the kinetic energy at impact (in Megatons and Joules), the recurrence interval time (i.e., the time between two consecutive impacts of the same energy), and the dimensions of the crater. Furthermore, the model provides the generated earthquake magnitude, the speed of the ejecta, the time they take to reach the ground, and their maximal altitude.

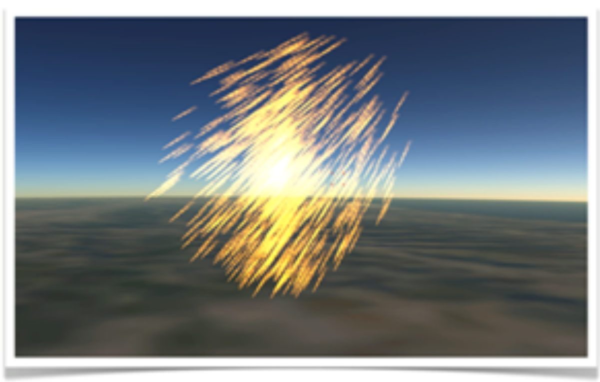

Figure 10 Screenshot of the videos made for the impact with Earth with fragmentation

For this phase, one of the main considered parameters has been the flight path velocity, which has been varied between 10 km/s and 30 km/s. This parameter has a great influence on the energy dissipated at impact and the corresponding consequences. The flight path angle has been kept at 45 degrees, representing an average impact angle.

Even if the occurrence of such scenarios is highly improbable, the fragmentation in the atmosphere of asteroids of diameter greater or equal than 10 km, has been simulated to show the power and flexibility of the tools and of the involved mathematical models.

Diameter [km]	Kin. energy at impact [MT]	Casualties [-]	Fatalities [-]	City
0.01	0.06	1.60	1.60	Tokyo
0.1	75.16	260.0	260.0	Amanu
1	7.52E+04	1,245.00	1,245.00	Verona
10	7.52E+07	2.38E+05	2.38E+05	Granada
100	7.52E+10	2.21E+07	2.21E+07	Houston

Table 3. Kinetic energy of the cases under study

8. PHASE 3: IMPACTING EARTH

This phase shows the collision with Earth at the impact point and the corresponding flight of ejecta around it (Figure 10 and *Figure 9*). In this phase, the study conducted a parametric analysis based on previous cases plus changing the impact velocity on Earth.

$$y = 470.12e^{0.1132x}$$

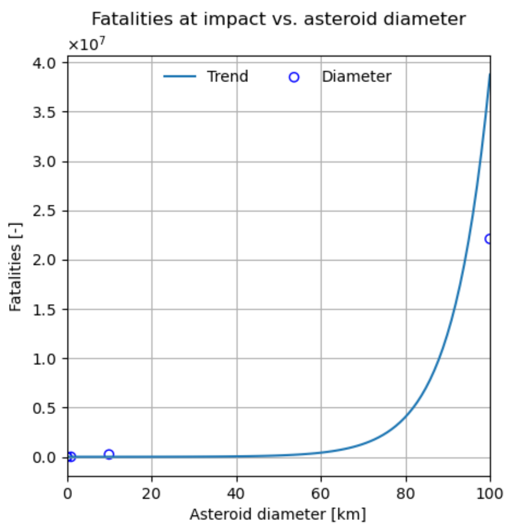

Figure 11 Casualties and fatalities per impact points. The computed fatality number takes into account only the people killed by a direct asteroid hit.

For this phase, the RAM module of ASTOS is used to calculate the casualty cross-section (Ac) of the asteroid. Ac is computed using the cross-section of all asteroid fragments and an average projected cross section of a human body. The probability of casualty is determined using this casualty cross-section, the impact probability, and a population density distribution map. The risk to the population on-ground is determined by integrating the probability over a terrain area with underlying population density. To calculate the fatality index by a given piece of fragment with a given kinetic energy, it is necessary to multiply the probability of impact by the fatality index.

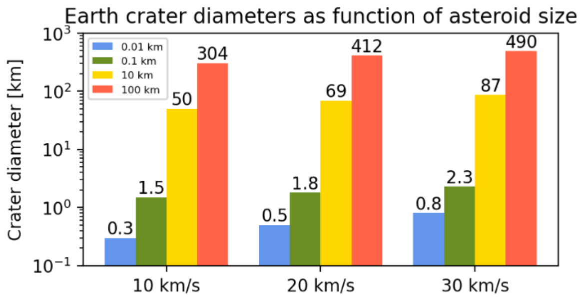

Figure 12. Earth craters diameters

The function found is a halved gaussian shaped curve that ends in an exponential (see *Figure 9*). The higher the value of the damage, the lower the probability that the damage actually occurs.

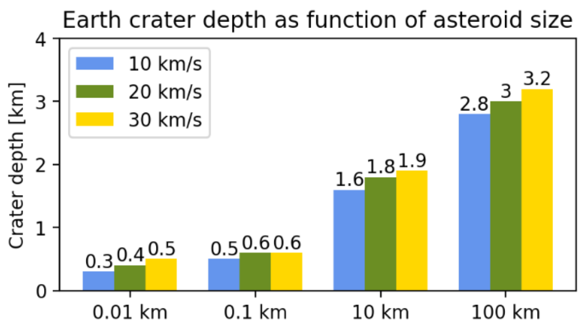

Figure 13. Earth craters depths

One of the computed cases is the un-fragmented impact in Granada. In this case, the energy released at impact is 7.5 x 10^7 MT (Megatons of TNT). The Earthquake produced has a magnitude of 9.9 Richter scale. The crater diameter is 69 km and has a depth of 1.8 km. The average ejecta thickness is 14.8 m. The mean fragment diameter is 5.43 cm. And the area of devastation at impact points is 107 km^2. For this Granada impact case, the wood frame and multi-story wall-bearing buildings will collapse. The interior partitions of wood frame buildings will be blown down. Roofs will be severely damaged. Multi-story steel-framed office-type buildings will suffer extreme frame distortion, mostly with incipient collapse. Highway truss and girder bridges will collapse. Cars and trucks will be overturned and displaced. Glass windows will shatter. And up to 90% of trees will be blown down, and those left standing will be stripped of branches and leaves.

9. PHASE 4: SHOCK WAVE

The phase four represents the shock wave and how it propagates on Earth from the impact point and in the direction of the foreseen azimuth. The simulation shows that the energy due to the impact will cause a distortion in the air. This distortion travels in the form of a shock wave, at a velocity greater than the speed of sound in air (hypersonic).

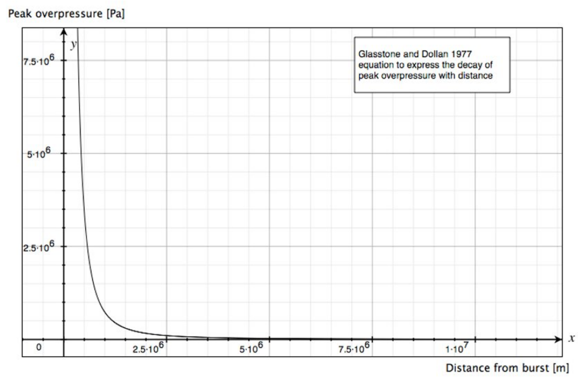

Figure 14 Shock wave propagation mathematical model. Glasstone and Dolan 1977 – Equation to express the decay of peak overpressure with distance.

10. PHASE 4+1: EFFECTS AFTER SHOCK WAVE

Figure 15 shows the fatality curve vs time in this phase.

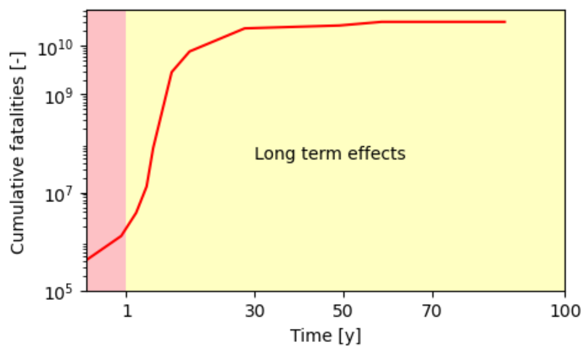

Figure 15 Cumulative fatalities curve vs time after shock wave

During the first sub-phase (post shock wave), dust, melt droplets, and gas species generated during the impact event are ejected out of the Earth's atmosphere and dispersed all over the globe. Also, during this sub-phase, tsunami cresting will reach 100 m altitude above sea level flooding 20 km inland from the coastline. During the second sub-phase (long-term effects), nitrous oxide will destroy the ozone layer causing more fatalities. At this stage, vision will not be possible, and plants and forest will die.

11. CONCLUSIONS

The Technical Directorate of ESA has built a mathematical model of an asteroid impacting with Earth. Using this model, the purpose of the study was to conduct a parametric analysis to calculate fatality curves as a function of the size of an asteroid colliding with Earth, its inner composition, its speed, its flight path angle at Earth entry, and its primary impact location on our planet.

Asteroid impacts represent low probability hazards but with severe consequences. Risk of impact is substantially larger than one-in-a-million by the lifetime risk of death, used in ESA terms when conducting the launch or re-entry of space vehicles.

It can be concluded, by the study here presented, that the impact of an asteroid, with diameter equal or larger than 10 km, would have catastrophic consequences, leading to the death of billions of people and producing a massive extinction of species (jeopardizing the survival of civilization [4], [5], [6]).

While the duties of governments in this context include the impact deflection, the impact mitigation, and catastrophe management, the duties of space agencies are limited to public awareness, threat detection, prediction, and risk analysis.

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