Dynamics of landslides on comet 67P/Churyumov–Gerasimenko. L. Czechowski[1] and K.J. Kossacki[2].
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Introduction: The phenomenon of landslide is a form of the gravity movement. They play important role in the overall process of erosion on the Earth and other terrestrial planets. Comets and other small celestial bodies have very weak gravity field, so it is believed that probability of such motion is very low. However data from space missions to comets 9P/Tempe 1 and 67P/Churyumov–Gerasimenko revealed existence of landslides.

The causes of landslides are usually related to instabilities of slopes. It is often possible to indicate a few causes of the landslide but usually only one factor is considered to be a trigger. Causes are the factors responsible for making the slope unstable in respect to small disturbances. For terrestrial landslides several causes are usually considered, e.g.:

(1) the pressure of water in pores acts usually to destabilize the slope,

(2) acceleration of ground motion resulting from earthquakes or impacts (it could add loads to barely stable slope),

(3) liquefaction of saturated soil could be a result of earthquake whereby the soil substantially loses its strength in response to an applied stress.

Some of these factors could also trigger the motion [1].

Note that on comets there are not liquid water nor vegetation. Instead of liquefaction one can expect rather fluidization when gas and solid particles form a mixture [2]. Such mixture are observed on the Earth as avalanche or pyroclastic density current.

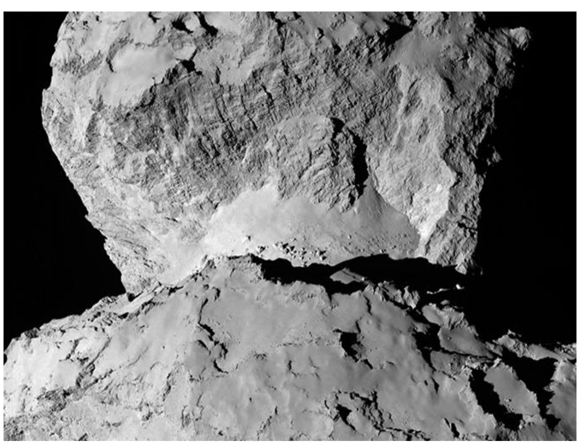

Fig. 1 Deposits resulting probably from landslides on the 67P/ Churyumov-Gerasimenko comet. ESA.

On the small bodies of spherical shape the total area of the regions with large slope (in respect to the local gravity) is rather limited. The different situation could be observed on highly asymmetric bodies [3]. In the present paper we consider comet 67P/Churyumov–Gerasimenko. Investigation of its nucleus indicated existence of deposit typical for landslides – Fig. 1. Moreover, on the Aswan cliff 1 meter fracture is observed.

Slopes of the surface: On the highly asymmetric comet determination of the slope of the surface is not a trivial problem. The gravitational field of 67P/Churyumov–Gerasimenko comet is very complicated. There are several regions of different slopes of the physical surface in respect to the gravity.

Table 2 presents area of considered surfaces where angle between the gravity and normal to the surface is in the given range. The normal to the surface is chosen to be towards the interior of the comet, so the angle $\alpha=0^{o}$ corresponds to the gravity perpendicular to the physical surface and directed toward the interior.

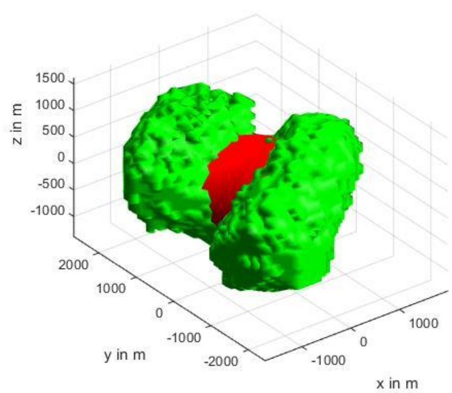

Fig. 2. Assumed mass distribution in the comet (green volume) and the surface of the constant value of the gravitational potential (red surface) for -0.45 $m^2 s^{-2}$. The green surface contains mass used for the modelling the gravity of the comet and it is close (but not identical) to the physical surface of the comet. Note highly non-spherical shapes of cometary surface of constant potential [3].

Table 2 indicates that the most of the surface (~75%) has the slope in the range $0< \alpha<40^{o}$. The slope in the range $40^{o} < \alpha<70^{o}$ is found on ~17% of the surface and on ~6% of the surface the slope is $70^{o} < \alpha<90^{o}$. On

~1.6% of the total are of the comet there are overhanging surfaces.

Table 2
Statistic of slope of the surface in respect to the gravity in the considered model.

Range	Part of total area	Number of faces
$0^{o} < \alpha \leq 10^{o}$	0.19	5757
$10^{o} < \alpha \leq 20^{o}$	0.25	9877
$20^{o} < \alpha \leq 30^{o}$	0.19	9452
$30^{o} < \alpha \leq 40^{o}$	0.11	6907
$40^{o} < \alpha \leq 50^{o}$	0.07	5057
$50^{o} < \alpha \leq 60^{o}$	0.06	4140
$60^{o} < \alpha \leq 70^{o}$	0.05	3409
$70^{o} < \alpha \leq 80^{o}$	0.04	2653
$80^{o} < \alpha \leq 90^{o}$	0.02	1579
$90^{o} < \alpha \leq 135^{o}$	0.015	1126
$135^{o} < \alpha \leq 180^{o}$	0.0005	37
Total	1.0	49994

Trajectories of ejecta: Here, we consider slow ejecta as material for the possible landslides. This ejecta could be a result of an internal activity [4, 5] or of impacts. We find that for the velocity 0.3 m s^{-1} or lower, the ejecta land usually close to the starting point. Ejecta faster than 0.5 m s^{-1} have complicated trajectories and could land very far from the starting point.

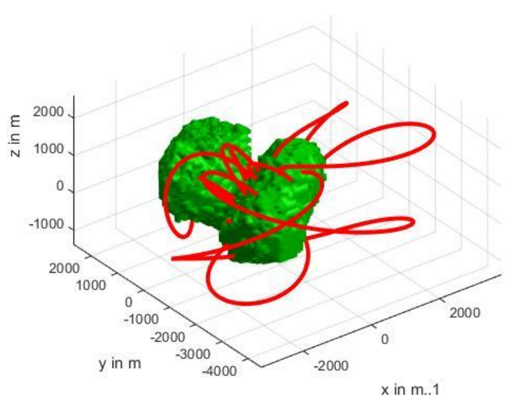

Fig. 3. Assumed mass distribution in the comet (green volume) and the trajectories of motion of the matter (red lines) ejected vertically (in respect to the physical surface) from 11 positions on the large lobe (right hand part on the figure) with the velocity 0.6 m s^{-1}. Note that the starting points of ejecta are on the upper surface of the lobe. Most of the landing points are on the upper surface on the large or small lobes. However, some trajectories reach also other sides of the comet.

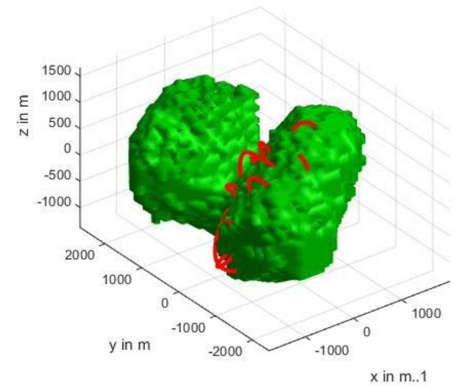

Fig. 4. The trajectories of motion of the matter ejected with the velocity 0.3 m s^{-1}. Note that the comet is presented in slightly different position comparing to other figures. The rest is as in Fig. 3.

Conclusion and future research: the dynamics of landslides formed by slow ejecta could be complicated. For the initial velocity higher than 0.6 m s^{-1} they could reach opposite side of the comet. Moreover, note that ejecta landing on the highly inclined surface could trigger another landslide. It depend on the properties of the material of the comet. These properties could be complicated [6]. We are going to investigate dynamics of such processes.

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