Study and modelling of rapid shoreline displacement due to coseismic subsidence along the Kamchatka subduction zone

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Abstract. The first studies of geological evidences of coastal coseismic subsidence (associated with subduction-zone earthquakes) were carried out in Russia at the Institute of Volcanology and Seismology, in Kamchatka. We developed a special method based on tephrostratigraphy and tephrochronology, descriptions and dating of the soil-pyroclastic sequence (SPS) overlying the coastal wave-build beach ridges. Three seismic events accompanied by coastal coseismic subsidence were detected in the northern part of Avachinsky Bay during the past ~5 thousand years. We found subsidence from one of the greatest historical tsunamiigenic earthquake (1952 AD) south of Petropavlovsk-Kamchatsky. We identified, that 5 events of coastal coseismic subsidence had occurred during the past ~6 thousand years at the coast of Kronotsky Bay and Shipunsky Peninsula. Amplitudes of subsidence were estimated by geological data using three different methods. Erosion of the active beach and marine accumulative terrace becomes active after coastal subsidence. We calculated the shoreline retreat process and the amount of horizontal erosion by numerical simulation using Bruun rule. In some areas, shoreline retreat was about 300 m according to the model results.

1. Introduction
Field studies of geological evidences of coastal coseismic subsidence were carried out on the Pacific coast of the Kamchatka Peninsula, the southern part of which is located along the Kuril-Kamchatka subduction zone, where earthquakes with ~ Mw 8 and higher occur quite often (figure 1). During our studies we have identified that sometimes mega-earthquakes with ~ Mw 9 and coseismic coastal subsidence associated with unusually wide source occurred at Kamchatka subduction zone. The occurrence of such events is about once in a thousand of years [1–6].

The geological evidences of coseismic subsidence were identified and studied on wave-built terraces consisting of a beach ridges sequence, between which there are trough, sometimes filled with marshes or lagoons. Such coastal relief is associated with a sediment supply, as a result of which the shoreline moves out toward the sea (prograding). On the coast of Avachinsky and Kronotsky bays the height of beach ridges is decreased landwards, or in other words, young beach ridges are higher than ancient ones. As a rule, this indicates a relative lowering of the land level, in the case of Kamchatka it is associated with the coseismic subsidence during great earthquakes in the subduction zone (the coast of Avachinsky Bay, for example (figure 2)). The study area, shown in Figure 2, extends for about 75 km from Mayachny Cape to the Shipunsky Peninsula. The width of the Holocene accumulative
terrace is from 500 to 2000 m. The age of the oldest beach ridges is about 5 thousand years [7]. Similar studies of vertical coseismic displacement were conducted on the coasts of Kronotsky Bay and Shipunsky Peninsula (in Morzhovaya Bay) (figure 2).

2. Methods
We studied the structure of beach ridges, which contain geological evidences of large seismic events, accompanied by vertical coseismic displacement (uplift and subsidence). The age of catastrophic earthquakes was estimated based on tephrochronology and radiocarbon dating of beach ridges deposits.

The development of the wave-built terrace under the influence of subduction earthquakes goes according to the following scenario [9, 5]: if there is enough sediment supply, the coastal shoreline moves seawards with the formation of new beach ridges (prograding). The shoreline begins to retreat after earthquake and subsidence; after a while (months or years), the equilibrium beach profile develops, and the shoreline stops to retreat, accumulative storm deposits overlap the active erosional scarp, this is how a buried scarp is forming (figure 3).

Figure 1. Location of the Kuril-Kamchatka subduction zone, with outlines of 20th century large and great Kamchatka earthquakes (modified after Gusev [8]). Heavy dashed lines indicate better located earthquake sources. PK – Petropavlovsk-Kamchatsky, BI – Bering Island. 1923 earthquakes are identified by month (Roman numerals) and day; e.g., 1923.II.24 is February 24, 1923 [5].

Figure 2. Study areas of geological evidences of coseismic subsidence (a); location of topographic profiles on the Avachinsky Bay coast, along which the excavations were made (b); topographic profiles across the marine accumulative terrace, with multicolored lines showing the identified buried scarps (c), the sea is on the right (modified from [5]).
Several methods have been developed to determine the amplitudes of coseismic displacement [9, 5]. After coseismic subsidence, the erosion of the coast was activated. Amount of coastal retreat were determined by numerical simulation according to Bruun rule [10].

\[
R = \frac{L}{B + h_s} S
\]

where \(R\) – shoreline horizontal displacement (retreat); \(S\) – sea level change; \(L\) – cross-shore distance to the depth of closure \(h_s\); \(B\) – berm height.

According to this rule, the coastal profile will be displaced landward or seaward, following to direction of the relative sea level change. The existence of accumulative beach is the result of the balance between wave energy, sediment supply (cross-shore, alongshore, from the river) and sea level. If there is a rapid rise in sea level, the balance is disturbed, that leads to a restructuring of the equilibrium beach and underwater profile. When the sea level rise, the shoreline retreat landward. If the sea level descends, the shore extends seaward. Estimating the volume of beach retreats due to coseismic displacement is an important aspect for studying coastal effects after the strongest earthquakes in subduction zone.

**Figure 3.** Method of dating paleo-beach ridges with tephra to estimate the age of buried erosional scarps/paleo earthquake (modified from [11]).

### 3. Results and discussing

All study sites on Avachinsky, Kronotsky and Shipunsky coasts are represented by marine accumulative terraces with beach ridges. Young beach ridges are higher than the old ones. Oldest beach ridges are not expressed in the relief and are identified either by vegetation or ground penetrating radar (GPR). As a rule, beach ridges are subdivided into series according to their height.

In places, where the height of the beach ridges changed, excavations were made to find and to describe buried scarps. They are geological evidences of coastal coseismic subsidence (associated with subduction-zone earthquakes). The scarps on the profiles are marked with multicolored lines (figure 2). Three seismic events accompanied by coastal coseismic subsidence were detected in the northern part of Avachinsky Bay during the past ~5 thousand years [5]. Five such events occurred at the coast of Kronotsky Bay and Shipunsky Peninsula during the past ~6 thousand years. [4]. The amplitudes of subsidence estimated from geological data did not exceed 2 meters and were usually within the range of 0.5–1 m. We modelled the shoreline retreat process and the amount of horizontal erosion for different amplitudes of subsidence. On the coast of Avachinsky Bay we obtained the following values: for 0.5 m surface subsidence, the value of coastal erosion was 72 m, for 1 m subsidence – 143 m, for 2 m – 287 m (table 1). South of Petropavlovsk-Kamchatsky, we found geological evidences of subsidence during one of the greatest historical tsunamigenic earthquake (1952 AD). The shoreline here still continues to erode. This is may be related either to insufficient amount of incoming sediment, or to the increase in the amplitude of subsidence to the
south, or to both of these factors [12]. On the coast of Kronotsky Bay and Shipunsky Peninsula, the calculated coastal erosion was 24–55 m for 0.5 m subsidence, 70–111 m for 1 m subsidence, and 200–221 m for 2 m subsidence (table 1).

### Table 1. Results of numerical simulation.

| Amplitude of coseismic coastal subsidence | Shore retreat by Bruun rule |
|------------------------------------------|-----------------------------|
|                                          | Avachinsky Bay              |
| 0.5                                      | 72                          |
|                                          | 24                          |
| 1                                        | 143                         |
|                                          | 70                          |
| 2                                        | 287                         |
|                                          | 200                         |

The data in the table show that the values of coastal retreat will be different for the same subsidence amplitudes in different sections. This may be due to both local features of the coast and different slope of the beach, as well as to the lack of versatility of the calculation model. The model does not take into account the features of morpho- and lithodynamics of the coast, in particular, the longshore sediment transport. In addition, in [13], standard coastal retreat trends were plotted for each section of Avachinsky Bay using the Bruun rule, which were subsequently compared with the results of coastal erosion calculations based on paleoseismological data from [5]. The comparison results are significantly different. The average coastal retreat, according to paleoseismological data, was 142 m, and according to the results of numerical simulation, 49 m [13]. Although in some areas the results of modelling and paleoseismological analysis coincide almost to 1 meter. We modified the Bruun model according to the coastal local features, based on geological and paleoseismological studies. The model is currently being finalized.

### 4. Conclusion

Shoreline displacements resulting from coseismic subsidence on Kamchatka (associated with subduction-zone earthquakes) have been simulated. The coastal retreats ranged from 24 to 287 m for typical in this region amplitudes of subsidence (0.5-2 m). These values can be used to predict the impact of the strongest earthquakes in the coasts of Kamchatka Peninsula. Modification the Bruun's rule of shoreline displacements as a result of relative sea level change for Kuril-Kamchatka region based on its verification with paleoseismological data is currently being developed.

On the coasts of the Kuril Islands, studies of the geological evidences of coseismic subsidence and numerical simulation of shoreline displacements have not yet been conducted. This task was set for the first time as a part of a new supported grant from the Russian Science Foundation (supervised by E.I. Gordeev). The first data were obtained during the 2021 field studies on Iturup Island. Detailed studies on Iturup Island are expected to be carry out in 2022. The study and modelling of shoreline changes during seismic events along the Kuril-Kamchatka subduction zone is very important for estimating the geomorphological impact of strongest earthquakes, especially for the areas with developing coastal infrastructure.

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