Inferring Shaking Intensities at Cemeteries that Have Suffered Multiple Damaging Earthquakes

Pioneer cemeteries in Alameda and Contra Costa Counties were strongly shaken by both the 1868 Hayward earthquake and the 1906 San Francisco earthquakes. By quantifying the damage to dated headstones and monuments, we can infer the intensity of ground shaking in both earthquakes at those cemeteries.

For cemeteries that suffer damage in only one earthquake, Boatwright and Bundock (2008) determined a robust relationship between the proportion of damaged gravestones d and the Modified Mercalli Intensity I_{MM}

$$I_{MM} = 3.33(d + 2.0) \qquad (1)$$

that fits cemetery damage for $7 \le I_{MM} \le 9$. We note that this relation is predicated on Stover and Coffman's (1993) revisions to the Modified Mercalli Intensity Scale.

For cemeteries that suffer damage in two earthquakes, such as the 1868 and the 1906 earthquakes, we can measure the proportional damage to the sets of pre-1868 and 1868-1906 gravestones, which we write as d_{12} and d_2, respectively. Table 1 shows a compilation of damage for five cemeteries in Alameda and Contra Costa Counties. Table 1 shows the number of broken, reset, and undamaged pre-1868 and 1868-1906 gravestones: the proportion of damaged gravestones is simply the number of broken and reset gravestones divided by the total of the broken, reset, and undamaged gravestones. Gravestones that cannot be damaged, such as cast zinc or short (> 0.3 m) stone desks, are not counted.

Table 1. Broken, Reset, and Undamaged Headstones and Monuments.

Cemetery	#brkn	#reset	#undg	%dmg	#brkn	#reset	#undg	%dmg	%cdm
	1868-1906 markers			d_2	pre-1868 markers			d_{12}	d_1
Mission San Jose	11	2	25	0.34	5	1	3	0.67	0.49
Alamo	7	7	18	0.44	8	3	6	0.65	0.37
Centerville	8	19	17	0.61	23	7	5	0.86	0.63
Lafayette	11	15	34	0.43	5	1	4	0.60	0.29
Mountain View	23	35	60	0.49	5	10	6	0.71	0.44

The damage to the pre-1868 gravestones d_{12} is the sum of the damage suffered in 1868 d_1 and the damage suffered in 1906 by the remaining (undamaged) gravestones $d_2'(1-d_1)$,

$$d_{12} = d_1 + d_2'(1-d_1). \tag{2}$$

This relation can be rewritten to estimate d_1 as

$$d_1 = (d_{12} - d_2')/(1-d_2'). \tag{3}$$

Obviously, the estimate of 1868 damage depends on the estimate of 1906 damage to the undamaged pre-1868 gravestones d_2'. While it seems natural to assume that the proportional damage to the surviving pre-1868 gravestones d_2' would be less than the proportional damage to the 1868-1906 gravestones d_2, Table 2 shows that the assumption $d_2' = d_2$ fits the 1868 intensities obtained from the towns near three cemeteries (Centerville, Alamo, and Mission San Jose), and gives reasonable estimates at the other two cemeteries (Lafayette and Mountain View in Oakland).

Table 2. Estimates of the Modified Mercalli Intensity

Cemetery	MMI 1868 C	MMI 1868	MMI 1906 C	MMI 1906
Mission San Jose	8	8	7-8	7-8
Alamo	7-8	7-8	8	-
Centerville	8-9	8-9	8-9	8
Lafayette	7-8	-	8	-
Mountain View	8	-	8	8

MMI 1868 C and MMI 1906 C are estimated from d_1 and d_2, respectively using equation (1), while MMI '68 and MMI '06 are taken from this document and from Boatwright and Bundock (2005).

We note that the assumption $d_2' = d_2$ minimizes the estimate of proportional damage to the 1868 gravestones. At the Lafayette and Alamo cemeteries, the damage and intensity estimates for the 1906 earthquake exceed those for the 1868 earthquake, while at the Centerville and Mountain View cemeteries, the damage and intensity estimates are the same for the two earthquakes. The estimate of the intensity for the 1906 earthquake at the Centerville cemetery is higher than the intensity determined for the town of Centerville by Boatwright and Bundock (2008) from F. Matthes' damage report in Lawson (1908). Although fenced, the cemetery is relatively accessible, however, and may have been damaged by vandalism during the 20th Century. If the vandalism post-dates the 1906 earthquake and was approximately uniform, then the estimate of proportional damage to the pre-1868 gravestones is not biased, even though the intensity for the 1906 earthquake is overestimated.