three-phase vertically segregated flows [7, 8, 9]. The interest in VE models diminished as computational resources increased. However, interface models for scenarios with strong gravity segregation (like steam injection) were also an active research area in the 80's and 90's [10, 11].

In recent years, there has been a renewed interest in VE methods as a means to simulate large-scale CO_2 migration, for which a sharp-interface assumption with vertical equilibrium may be reasonable. Many authors have developed analytical solutions to study different aspects of CO_2 injection, assuming rapid vertical segregation and vertical equilibrium [12, 4, 1, 13, 14, 15, 16]. In particular Gasda et al. [17], extended a VE formulation with sub-scale analytic functions and demonstrated the potential of using a VE formulation to speed up simulations of CO_2 migration. Numerical calculations using a VE formulation compared well with full 3D simulations in a recent benchmark study [18].

Herein, we investigate the use of VE models for a realistic large-field case based on data from the Sleipner site. Our calculations consider the effects of hydrodynamic and residual trapping. We discuss the potential and limitations of VE models and show how VE models can be combined with standard methods to give reliable results both for the plume development (injection stage) and plume migration (post injection). Particularly, we focus on a model that incorporates the aquifer geometry and heterogeneity in a flexible way that enables us to utilize 3D simulations whenever needed, for example, for the injection period in heterogeneous reservoirs. To investigate large-scale CO_2–injection projects with realistic rock properties over long time periods, it is crucial to reduce the computational cost. VE models enables this by using analytical solutions to capture the vertical features in the flow system, thereby reducing the dimensionality of the problem. Achieving the same in a three dimensional simulation requires prohibitively high vertical resolution.

The main objective of this paper is to compare simulations of CO_2 migration in the Utsira formation in the North Sea using a standard three-dimensional reservoir simulator and two-dimensional VE formulations. To our knowledge, this is one of the first comparisons between full-3D and VE calculations for a real CO_2 injection site. Our aims are to demonstrate the benefits of using a VE model to simulate CO_2 migration in a realistic setting and to discuss how VE models can be used to develop fast techniques to simulate CO_2 injection at the basin scale.

2. Mathematical formulation

In this section we present a brief summary of the derivation of a vertical equilibrium formulation. A more thourough derivation can be found in [19]. First, we assume that CO_2 migration in saline aquifers can be modeled as a two-phase problem with brine and CO_2 as the wetting (w) and non-wetting (n) fluids, respectively. Furthermore, we consider the evolution of a CO_2 plume in an aquifer whose mean direction makes a constant dip angle θ with the horizontal plane as shown in Figure 1. We start the derivation by writing a mass conservation

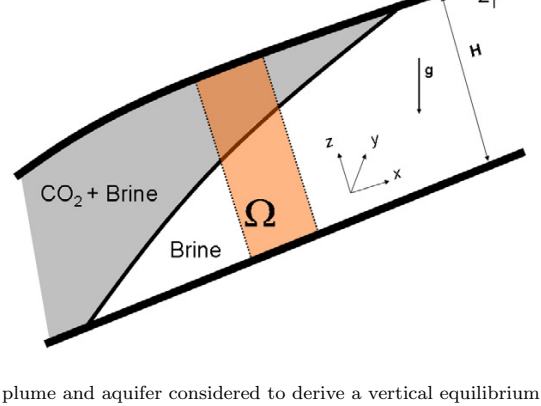

Figure 1: Schematic of the CO_2 plume and aquifer considered to derive a vertical equilibrium formulation for CO_2 migration.

equation for each fluid phase inside control volume $\Omega = \Delta x \Delta y H$ to obtain

$$\frac{\partial}{\partial t} \int_{\Omega} \phi s_\alpha + \int_{\partial\Omega} \mathbf{f}_\alpha = \int_{\Omega} q_\alpha, \tag{1}$$

where s_α is the core-scale saturation of phase α, ϕ is the rock porosity, $\mathbf{f}_\alpha$ are the fluid fluxes that pass through the control volume boundaries and q_α represents source and/or sink terms. Taking the limit $\Delta x, \Delta y \to 0$ and