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Γ -convergence for a Mumford-Shah functional adapted to a segmentation problem

David Vicente

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Abstract

We consider a segmentation problem of image close to a binary one. After introducing a Mumford Shah energy like, we perform an approximation of this model. We prove a Γ -convergence result and show why this approximation is suitable for numerics.

1 Introduction

This paper is motivated by a 3D-image segmentation process with thin tubular structures. We have introduced a model which is derived from Mumford and Shah's one in [?]. Mathematical analysis of such model is difficult. So, in order to make numerical experiments, we perform an approximation in the sense of Γ -convergence. More precisely, an image is modeled as an application g defined on Ω with values on $[0, 1]$ where Ω is an open, bounded and regular subset of \mathbb{R}^n . We assume that g is close to a binary function. More precisely, its histogram has two distincts modes that we assume to be 0 and 1. We prove that the model

$$(\mathcal{P}): \quad \text{Min} \{E(p): p \in SBV(\Omega), p(x) \in \{0; 1\} \text{ a.e. } x \in \Omega\}, \quad (1.1)$$

where $E(p) = \frac{1}{2} \int_{\Omega} (p - g)^2 dx + \beta \mathcal{H}^{n-1}(S_p)$.

where S_p is the jump set of the binary function p , may be approximated by

$$(\mathcal{P}_{\varepsilon}): \quad \text{Min} \{E_{\varepsilon}(p): p \in W^{1,2}(\Omega), 0 \leq p(x) \leq 1 \text{ a.e. } x \in \Omega\}$$

where $E_{\varepsilon}(p) = \frac{1}{2} \int_{\Omega} (p - g)^2 dx + \beta \int_{\Omega} \left(9\varepsilon |\nabla p|^2 + \frac{p^2(1-p)^2}{\varepsilon} \right) dx$

(1.2)

in the sense of the Γ -convergence. In the application which motivated this paper, we set $n = 3$ but we prove this result for any $n \geq 1$.

In a companion paper [?] we perform a tuning for the parameters of this approximated model in order to detect thin structures of tubes in 3D images and we give there a complete bibliography of the subject. In the present paper we introduce the theoretical framework (section ??) then we prove the Γ -convergence of the model (section ??) and give additional properties related to numerical aspects (section ??).

2 Functional framework and Γ -convergence

2.1 Functional spaces

We work in this paper with spaces of functions with bounded variation that we recall thereafter, for more details see [?], [?].

Definition 2.1. *Let Ω be an open subset \mathbb{R}^n , and $u \in L^1(\Omega)$. We define $BV(\Omega)$, the space of functions with bounded variations:*

$$BV(\Omega) = \{u \in L^1(\Omega) : TV(u) < +\infty\},$$

where

$$TV(u) = \sup \left\{ \int_{\Omega} u(x) \operatorname{div}(\xi)(x) dx : \xi \in C_c^1(\Omega), \|\xi\|_{\infty} \leq 1 \right\}.$$

The space $BV(\Omega)$, with the norm $\|u\|_{BV(\Omega)} = \|u\|_{L^1} + TV(u)$, is a Banach space. The derivative, in a distributional sense, of an element $u \in BV(\Omega)$ is a Radon measure, denoted Du , and $TV(u) = \int_{\Omega} |Du|$ is the total variation of u . We introduce the following notation for a measure μ and a set B , $\mu \llcorner B$ is the measure such that:

$$\mu \llcorner B(A) = \mu(A \cap B).$$

We recall useful properties on the structure of the gradient of BV functions in next theorem.

Theorem 2.1. *Let $u \in BV(\Omega)$ then we have the following decomposition:*

$$Du = \nabla u \cdot \mathcal{L}_n + (u^+ - u^-) \nu_u \mathcal{H}^{n-1} \llcorner S_u + C_u,$$

where

- $\nabla u = \frac{Du}{\mathcal{L}_n}$,
- S_u is a countable union of hypersurfaces,
- $\nu_u : S_u \rightarrow \mathbf{S}^{n-1}$ is a measurable normal unitary vector of S_u ,
- u^-, u^+ are the lower and upper approximated limits of u ,
- $C_u \perp \mathcal{H}^{n-1}$.

Definition 2.2. *For any $u \in BV(\Omega)$, we set:*

- $\nabla u \cdot \mathcal{L}_n$ as the regular part of Du ,
- S_u as the jump set of u ,
- $(u^+ - u^-) \nu_u \mathcal{H}^{n-1} \llcorner S_u$ as the jump part of Du ,

- C_u as the Cantor part of Du .

Definition 2.3. The set of BV -functions whose derivative have a Cantor part equal to zero is called the special set of functions with bounded variation, denoted $SBV(\Omega)$.

Theorem 2.2. Let $u = \mathbf{1}_A$ an indicator function such that $u \in SBV(\Omega)$ then we have the following decomposition:

$$Du = \nu_u \mathcal{H}^{n-1} \llcorner S_u.$$

The space SBV has a useful slicing property.

Definition 2.4. Let $\nu \in \mathbf{S}^{n-1}$ (unit sphere of \mathbb{R}^n) and Ω be an open subset of \mathbb{R}^n . Let Π_ν be the orthogonal plane to ν :

$$\Pi_\nu = \{x \in \mathbb{R}^n : \langle \nu, x \rangle = 0\},$$

where $\langle \cdot, \cdot \rangle$ stands for the scalar \mathbb{R}^n -product. For any $x \in \Pi_\nu$ we define

$$\Omega_x = \{t \in \mathbb{R} : x + t\nu \in \Omega\}$$

and

$$\Omega_\nu = \{x \in \Pi_\nu : \Omega_x \neq \emptyset\},$$

see figure ??.

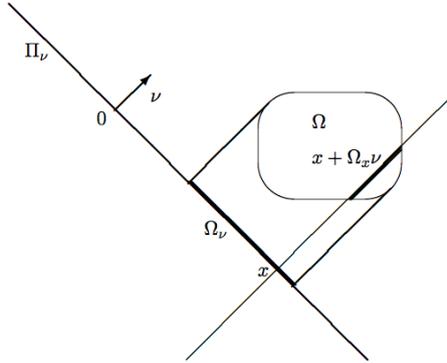


Figure 2.1: Slicing the open Ω

As in [?], we introduce a projection on the open set Ω_x (see figure ??). For any function u defined on $\Omega \subset \mathbb{R}^n$ and any $x \in \Omega_\nu$, we set

$$\begin{aligned} u_x: \Omega_x &\rightarrow \mathbb{R} \\ t &\rightarrow u(x + t\nu) \end{aligned}$$

Theorem 2.3. Let $u \in L^\infty(\Omega)$ be a function such that, for all $\nu \in \mathbf{S}^{n-1}$,

i) $u_x \in SBV(\Omega_x)$ for \mathcal{H}^{n-1} a.e. $x \in \Omega_\nu$,

ii) $\int_{\Omega_\nu} \left\{ \int_{\Omega_x} |\nabla u_x| dt + \mathcal{H}^0(S_{u_x}) \right\} d\mathcal{H}^{n-1}(x) < +\infty$ where S_v is the jump set of the function v (see ??);

then, $u \in SBV(\Omega)$ and $\mathcal{H}^{n-1}(S_u) < +\infty$.

Conversely, let $u \in SBV(\Omega) \cap L^\infty$ be such that $\mathcal{H}^{n-1}(S_u) < +\infty$. Then i) and ii) are satisfied. Moreover, we have

iii) $\langle \nabla u(x + t\nu), \nu \rangle = \nabla u_x(t)$, for a.e. $t \in \Omega_x$ and \mathcal{H}^{n-1} -a.e. $x \in \Omega_\nu$,

iv) there exists a measurable function $\nu_u : S_u \rightarrow \mathbf{S}^{n-1}$ depending on S_u , such that

$$\int_{S_u} \langle \nu_u, \nu \rangle d\mathcal{H}^{n-1}(x) = \int_{\Omega_\nu} \mathcal{H}^0(S_{u_x}) d\mathcal{H}^{n-1}(x).$$

2.2 Γ -convergence theory

Usually, a standard compactness argument is sufficient to prove the existence of minimizing solutions. In our case, we use a specific notion of convergence which will be specified here, since compactness is not ensured for usual topologies. As before, for more details see [?].

Definition 2.5. Let (X, d) a metric space, $(F_n)_{n \in \mathbb{N}}$ a sequence of functions defined on X with values in $\mathbb{R} \cup \{+\infty\}$ and $F : X \rightarrow \mathbb{R} \cup \{+\infty\}$. The sequence $(F_n)_{n \in \mathbb{N}}$ Γ -converges to F on $x \in X$ if the following assertions are true:

i) for all $(x_n)_{n \in \mathbb{N}}$ which converges to x :

$$F(x) \leq \liminf_{n \rightarrow \infty} F_n(x_n),$$

ii) there exists $(y_n)_{n \in \mathbb{N}}$ which converges to x such that:

$$F(x) \geq \limsup_{n \rightarrow \infty} F_n(y_n),$$

This concept is the convergence of the approximate minimum. More precisely, if for any n , p_n is a minimum of F_n and $(p_n)_n$ converges to p , then according to this concept, p is a minimum of F .

We shall use the following result.

Proposition 2.1. Let X a topological space, $(f_n)_{n \in \mathbb{N}}$ a sequence of functions defined on X with values in $\mathbb{R} \cup \{+\infty\}$ which Γ -converges to f and h a continuous function defined on X with values in $\mathbb{R} \cup \{+\infty\}$. Then the sequence $(f_n + h)_{n \in \mathbb{N}}$ Γ -converges to $f + h$.

3 A Γ -convergence result

We now prove that the family of functionals $(E_\varepsilon)_{\varepsilon>0}$ defined by (??) Γ -converges to E defined by (??). For more simplicity in the proof we assume that $\beta = 1$ in this section, its value doesn't change the arguments of the proof. We denote $W_b^{1,2}(\Omega)$ the following space

$$W_b^{1,2}(\Omega) = \left\{ p \in W^{1,2}(\Omega) : 0 \leq p(x) \leq 1 \text{ a.e. } x \in \Omega \right\}.$$

Let $\mathbb{B}(\Omega; [0, 1])$ be the space of measurable functions defined on Ω which take their values in $[0, 1]$. This space is endowed with the almost everywhere convergence topology. It's a Fréchet space (see [?]).

Let F be the penalization term of the functional E :

$$F: \mathbb{B}(\Omega; [0, 1]) \rightarrow \mathbb{R} \cup \{+\infty\} \quad (3.1)$$

$$p \mapsto \begin{cases} \mathcal{H}^{n-1}(S_p) & \text{if } p \in SBV(\Omega), \\ +\infty & \text{otherwise} \end{cases} \quad (3.2)$$

and F_ε be its approximation:

$$F_\varepsilon: \mathbb{B}(\Omega; [0, 1]) \rightarrow \mathbb{R} \cup \{+\infty\}$$

$$p \mapsto \begin{cases} \int_\Omega \left(9\varepsilon |\nabla p|^2 + \frac{p^2(1-p)^2}{\varepsilon} \right) dx, & \text{if } p \in W_b^{1,2}(\Omega), \\ +\infty & \text{otherwise.} \end{cases}$$

Let H be the fitting data term:

$$H: \mathbb{B}(\Omega; [0, 1]) \rightarrow \mathbb{R} \cup \{+\infty\}$$

$$p \rightarrow \frac{1}{2} \int_\Omega (p - g)^2 dx.$$

Let $(p_k)_{k \in \mathbb{N}} \subset \mathbb{B}(\Omega; [0, 1])$ be a a.e. converging sequence to some p . According Lebesgue theorem and the fact that $\|p_k\|_\infty \leq 1$, the sequence $(H(p_k))_{k \in \mathbb{N}}$ converges to $H(p)$ and H is continuous for the almost everywhere convergence topology. So, it is sufficient to prove the Γ -convergence of F_ε to F . Indeed, proposition ?? with $X = \mathbb{B}(\Omega; [0, 1])$, implies the Γ -convergence of $E_\varepsilon = F_\varepsilon + H$ to $E = F + H$.

We introduce the following notation:

$$F_\varepsilon(p, U) = \int_U \left(9\varepsilon |\nabla p|^2 + \frac{p^2(1-p)^2}{\varepsilon} \right) dx, \quad F(p, U) = \mathcal{H}^{n-1}(S_p \cap U)$$

and

$$F_-(p, U) = \inf \left\{ \liminf_{k \rightarrow \infty} F_{\varepsilon_k}(p_k, U) \mid p_k \xrightarrow{a.e.} p, (p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(U) \right\}. \quad (3.3)$$

The functional F_- is also called the *lower- Γ limit* of F .

We shall prove the following theorem.

Theorem 3.1. *Let $(\varepsilon_k)_{k \in \mathbb{N}}$ be a sequence which converges to 0^+ and $p \in SBV(\Omega)$ be a function taking its values in $\{0, 1\}$. Then*

$$i) \quad F(p, \Omega) \leq F_-(p, \Omega) \quad (3.4)$$

holds;

ii) there exists a sequence $(p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ which converges a.e. to p such that:

$$F(p, \Omega) \geq \limsup_{k \rightarrow \infty} F_{\varepsilon_k}(p_k, \Omega). \quad (3.5)$$

According to this theorem, we deduce that $F(p, \Omega) = F_-(p, \Omega)$ for $p \in SBV(\Omega)$ taking its values in $\{0, 1\}$. The proof is detailed thereafter.

3.1 The inequality for the lower Γ -limit (??)

We now prove the first inequality (??). We shall need the following properties of this functional:

a) $F_-(p, \cdot)$ is superadditive on open sets, that is

$$A \cap B = \emptyset \quad \Rightarrow \quad F_-(p, A \cup B) \geq F_-(p, A) + F_-(p, B),$$

b) $F_-(p, \cdot)$ is non decreasing:

$$A \subset B \quad \Rightarrow \quad F_-(p, A) \leq F_-(p, B).$$

By a diagonal extraction, there exists a sequence $(p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ such that:

$$\begin{cases} p_k \xrightarrow{a.e.} p, \\ F_{\varepsilon_k}(p_k, \Omega) \rightarrow F_-(p, \Omega) \end{cases} \quad (3.6)$$

We assume that $F_-(p, \Omega) < +\infty$ otherwise (??) is ensured. We have to prove:

$$F(p, \Omega) \leq \liminf_{k \rightarrow \infty} F_{\varepsilon_k}(p_k, \Omega)$$

As in [?], we perform the proof in two steps: the first step deals with dimension 1. The second generalizes it for dimension $n \geq 2$.

3.1.1 The one-dimensional case

Assume $\Omega = I$ is an open interval. To avoid confusion, when $n = 1$, we denote the approximating functionals by F_ε^1 et their lower Γ -limit, defined in (??), by F_-^1 .

Lemma 3.1. *Let $B_\eta(x) \subset \mathbb{R}$ be an open ball and $q \in \mathbb{B}(B_\eta(x))$ be a function taking its values in $\{0; 1\}$. Assuming*

$$\forall \rho \in]0, \eta[, \quad q \notin W^{1,2}(B_\rho(x)),$$

then we have:

$$\forall \rho \in]0, \eta[, \quad F_-^1(q, B_\rho(x)) \geq 1.$$

In particular, if $I \subset \mathbb{R}$ is an open and bounded interval such that $q \in \mathbb{B}(I)$ takes its values in $\{0; 1\}$ and $F_-^1(q, I) < +\infty$ then $q \in SBV(I)$. Moreover, there exists $J \subset I$ with cardinal less than $F_-^1(q, I)$ such that

i) p is constant on each connected component of $I \setminus J$,

ii) $\mathcal{H}^0(S_q \cap I) \leq F_-^1(q, I)$.

Proof. We can assume that $F_-^1(q, B_\rho(x)) < +\infty$ for any $\rho \in]0; \eta[$. As before, there exists a sequence $(q_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(B_\rho(x))$ such that:

$$\begin{cases} q_k \xrightarrow{\text{a.e.}} q, \\ F_{\varepsilon_k}^1(q_k, B_\rho(x)) \rightarrow F_-^1(q, B_\rho(x)) \end{cases} \quad (3.7)$$

Since q takes its values a.e. in $\{0, 1\}$ and $q \notin W^{1,2}(B_{\rho'}(x))$ for any $\rho' \in]0, \rho[$, there exists two sequences $(y_k^1)_{k \in \mathbb{N}}$ and $(y_k^2)_{k \in \mathbb{N}}$ such that:

$$y_k^1 \rightarrow x, \quad q_k(y_k^1) \rightarrow 1 \quad \text{and} \quad y_k^2 \rightarrow x, \quad q_k(y_k^2) \rightarrow 0.$$

However, we have:

$$F_{\varepsilon_k}^1(q_k, B_\rho(x)) \geq \int_{x-\rho}^{x+\rho} \left(9\varepsilon_k |\nabla q_k(y)|^2 + \frac{q_k^2(1 - q_k(y))^2}{\varepsilon_k} \right) dy.$$

We introduce:

$$A := 3\sqrt{\varepsilon_k} |\nabla q_k(y)|, \quad B := \frac{q_k(1 - q_k(y))}{\sqrt{\varepsilon_k}}.$$

With the inequality $A^2 + B^2 \geq 2AB$, we get:

$$F_{\varepsilon_k}^1(q_k, B_\rho(x)) \geq 6 \int_{x-\rho}^{x+\rho} |\nabla q_k(y)| q_k(y) (1 - q_k(y)) dy.$$

As $[y_k^1, y_k^2] \subset B_\rho(x)$, we obtain:

$$F_{\varepsilon_k}^1(q_k, B_\rho(x)) \geq 6 \int_{y_k^1}^{y_k^2} |\nabla q_k(y)| q_k(y) (1 - q_k(y)) dy.$$

Since $q_k \in W^{1,2}(I)$, we may use the change of variable $t = q_k(s)$. This yields:

$$\begin{aligned} F_{\varepsilon_k}^1(q_k, B_\rho(x)) &\geq 6 \int_{q_k(y_k^1)}^{q_k(y_k^2)} t(1-t) dt, \\ F_{\varepsilon_k}^1(q_k, B_\rho(x)) &\geq 6 \left| \frac{q_k^2(y_k^1) - q_k^2(y_k^2)}{2} - \frac{q_k^3(y_k^1) - q_k^3(y_k^2)}{3} \right| \end{aligned}$$

We know that $q_k(y_k^1) \rightarrow 1$ and $q_k(y_k^2) \rightarrow 0$, so that we deduce:

$$\frac{q_k^2(y_k^1) - q_k^2(y_k^2)}{2} - \frac{q_k^3(y_k^1) - q_k^3(y_k^2)}{3} \rightarrow \frac{1}{6}.$$

It comes,

$$\liminf F_{\varepsilon_k}^1(q_k, B_\rho(x)) \geq 1.$$

and we can conclude

$$F_-^1(q, B_\rho(x)) \geq 1. \quad (3.8)$$

We set

$$J = \left\{ x \in I : \forall \rho > 0, q \notin W^{1,2}(B_\rho(x)) \right\}.$$

The functional $F_-^1(q, \cdot)$ is super-additive and non-decreasing (see (??)). With inequality (??) we get

$$F_-^1(q, I) \geq \mathcal{H}^0(J).$$

According to the fact that q takes its values a.e. in $\{0; 1\}$, then q is constant on the connected components of $I \setminus J$ and $S_q \cap I = J$. Therefore, we may conclude

$$F_-^1(q, I) \geq \mathcal{H}^0(S_q \cap I).$$

□

3.1.2 Generalization to dimensions $n \geq 2$

We now extend the proof to any higher dimension n by a slicing argument.

Recall that we want to prove $F_-(p, \Omega) \geq F(p, \Omega)$.

Let $(p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ as in (??). Let A be an arbitrary open subset of Ω . Assume that $F_-(p, A) < +\infty$ and $F_{\varepsilon_k}(p_k, A) \rightarrow F_-(p, A)$. Let $\nu \in \mathbf{S}^{n-1}$ be an unit vector, we have:

$$\begin{aligned} F_{\varepsilon_k}(p_k, A) &= \int_A \left(9\varepsilon_k |\nabla p_k(x)|^2 + \frac{p_k^2(x)(1-p_k(x))^2}{\varepsilon_k} \right) dx \\ &\geq \int_A \left(9\varepsilon_k |\langle \nabla p_k(x), \nu \rangle|^2 + \frac{p_k^2(x)(1-p_k(x))^2}{\varepsilon_k} \right) dx \end{aligned}$$

The Lebesgue measure of \mathbb{R}^n projected on Π_ν is the Hausdorff measure with dimension $n - 1$ (see for example [?]). Applying Fubini theorem, we get:

$$\begin{aligned} F_{\varepsilon_k}(p_k, A) &\geq \int_{A_\nu} \int_{A_x} \left(9\varepsilon_k |\langle \nabla p_k(x + t\nu), \nu \rangle|^2 + \frac{p_k(x + t\nu)^2 (1 - p_k(x + t\nu))^2}{\varepsilon_k} \right) dt \, d\mathcal{H}^{n-1}(x) \\ &\geq \int_{A_\nu} F_{\varepsilon_k}^1((p_k)_x, A_x) \, d\mathcal{H}^{n-1}(x). \end{aligned}$$

Fatou lemma yields:

$$F_-(p, A) \geq \int_{A_\nu} \liminf F_{\varepsilon_k}^1((p_k)_x, A_x) \, d\mathcal{H}^{n-1}(x).$$

As $(p_k)_x \in SBV(A_x)$ a.e. $x \in A_\nu$, with lemma ??, we have:

$$F_-(p, A) \geq \int_{A_\nu} \mathcal{H}^0(S_{(p)_x} \cap A_x) \, d\mathcal{H}^{n-1}(x).$$

Using theorem ?? gives:

$$\int_{A_\nu} \mathcal{H}^0(S_{(p)_x} \cap A_x) \, d\mathcal{H}^{n-1}(x) = \int_{S_p \cap A} |\langle \nu_p, \nu \rangle| \, d\mathcal{H}^{n-1}(x),$$

so that

$$F_-(p, A) \geq \int_{S_p \cap A} |\langle \nu_p, \nu \rangle| \, d\mathcal{H}^{n-1}(x). \quad (3.9)$$

As p belongs to $SBV(\Omega)$, according to theorem ??, the set S_p is a countable union of \mathcal{C}^1 -hypersurfaces. Then, we obtain:

$$\mathcal{H}^{n-1}(S_p) = \sup_{\mathcal{A}, \mathcal{V}} \left\{ \sum_{i=1}^{\infty} \int_{S_p \cap A_i} |\langle \nu_p, \nu_i \rangle| \, d\mathcal{H}^{n-1}(x) \right\}$$

where the supremum is taken over all the families $\mathcal{A} = (A_i)_{i=1 \dots \infty}$ of open and pairwise disjoint subsets of Ω and $\mathcal{V} = (\nu_i)_{i=1 \dots \infty} \subset \mathbf{S}^{n-1}$. Applying the inequality (??) to each term, we have:

$$\mathcal{H}^{n-1}(S_p) \leq \sup_{\mathcal{A}} \left\{ \sum_{i=1}^{\infty} F_-(p, A_i) \right\}.$$

where the supremum is only taken over all the families \mathcal{A} .

Since $F_-(p, \cdot)$ is super-additive and non decreasing (see (??)), then we may conclude that

$$\mathcal{H}^{n-1}(S_p) \leq F_-(p, \Omega).$$

□

3.2 The inequality for the *higher* Γ -limit (??)

To prove the second part (??), we construct a sequence of functions $(p_k)_{k \in \mathbb{N}}$ converging to p , so that the higher bound of the energy is lower than $F(p, \Omega)$. We will use the following lemma due to Modica [?].

Lemma 3.2. *Let A be an open and bounded subset of Ω with a non empty Lipschitz boundary ∂A . Let*

$$h(x) = \begin{cases} +\text{dist}(x, \partial A) & \text{if } x \in A, \\ -\text{dist}(x, \partial A) & \text{otherwise} \end{cases}$$

and for all $t > 0$, $S_t = \{x \in A : h(x) = t\}$.

Then h is a Lipschitz function, and we have:

$$|Dh(x)| = 1 \text{ a.e. } x \in \Omega \text{ and } \lim_{t \rightarrow 0} \mathcal{H}^{n-1}(S_t \cap \Omega) = \mathcal{H}^{n-1}(\partial A \cap \Omega).$$

We may now prove the second part (??) of theorem ??.

Proof. Set:

$$h(x) = \begin{cases} +\text{dist}(x, \{p = 0\}) & \text{if } p(x) = 1, \\ -\text{dist}(x, \{p = 1\}) & \text{if } p(x) = 0, \end{cases}$$

$$\chi_0(t) = \begin{cases} 1 & \text{si } t \geq 0, \\ 0 & \text{si } t < 0. \end{cases}$$

It is clear that $p = \chi_0 \circ h$. We construct p_k as $p_k = \chi_k \circ h$. In this case, we have:

$$F_{\varepsilon_k}(p_k) = \int_{\Omega} \left(9\varepsilon_k |\nabla \chi_k(h(x))|^2 |\nabla h(x)|^2 + \frac{\chi_k^2(h(x))(1 - \chi_k(h(x)))^2}{\varepsilon_k} \right) dx.$$

The function p belongs to $SBV(\Omega)$. According to theorem ?? and lemma ??, we have $|\nabla h(x)| = 1$ for almost every $x \in \Omega$. Then, we may apply coarea formula (see for example [?]) to obtain:

$$F_{\varepsilon_k}(p_k) = \int_{t=-\infty}^{+\infty} \varphi_{\varepsilon,k}(t) \mathcal{H}^{n-1}(\{h = t\}) dt,$$

where
$$\varphi_{\varepsilon,k}(t) = 9\varepsilon_k |\nabla \chi_k(t)|^2 + \frac{\chi_k^2(t)(1 - \chi_k(t))^2}{\varepsilon_k}.$$

The minimization of this energy is a 1D-problem. The Euler-lagrange equation associated to this problem is:

$$(9\varepsilon_k (\chi_k')^2)' = \left(\frac{\chi_k^2(1 - \chi_k)^2}{\varepsilon_k} \right)'$$

Thus, there exists $c_k > 0$ such that:

$$9\varepsilon_k(\chi'_k)^2 = c_k + \frac{\chi_k^2(1-\chi_k)^2}{\varepsilon_k} \quad (3.10)$$

Let $\overline{\chi}_k$ a solution of the equation (??) such that:

$$\begin{cases} \overline{\chi}_k(t) = 0 & \text{if } t \leq 0, \\ 3\sqrt{\varepsilon_k}\overline{\chi}'_k = \sqrt{c_k + \frac{\overline{\chi}_k^2(1-\overline{\chi}_k)^2}{\varepsilon_k}} & \text{if } t \in [0, \eta_k], \\ \overline{\chi}_k(t) = 1 & \text{if } t \geq \eta_k. \end{cases}$$

As $\overline{\chi}'_k \geq \sqrt{\frac{c_k}{9\varepsilon_k}}$, we have $\eta_k \leq \sqrt{\frac{c_k}{9\varepsilon_k}}$. If $\frac{c_k}{\varepsilon_k} \rightarrow 0$ then $\overline{\chi}_k \circ h$ converges to p almost everywhere.

Set $A = 3\sqrt{\varepsilon_k}\overline{\chi}'_k$ and $B = \frac{\overline{\chi}_k(1-\overline{\chi}_k)}{\sqrt{\varepsilon_k}}$. We have $A^2 = c_k + B^2$ and

$$\begin{aligned} A^2 + B^2 &= 2AB + c_k + 2B^2 - 2AB, \\ &= 2AB + c_k + 2B(B - A), \\ &= 2AB + c_k + 2B(B - \sqrt{c_k + B^2}), \\ &= 2AB + c_k - 2c_k \frac{B}{B + \sqrt{c_k + B^2}}. \end{aligned}$$

Replacing it in $F_{\varepsilon_k}(p_k)$ leads to:

$$\begin{aligned} F_{\varepsilon_k}(p_k) &= \int_{t=0}^{\eta_k} (A^2 + B^2) \mathcal{H}^{n-1}(\{h = t\}) \, dt \\ &= \int_{t=0}^{\eta_k} (2AB + c_k - 2c_k \frac{B}{B + \sqrt{c_k + B^2}}) \mathcal{H}^{n-1}(\{h = t\}) \, dt \\ &\leq \int_{t=0}^{\eta_k} (2AB + c_k) \mathcal{H}^{n-1}(\{h = t\}) \, dt. \end{aligned}$$

Replacing A and B by its values, we get:

$$F_{\varepsilon_k}(p_k) \leq \int_{t=0}^{\eta_k} 6\overline{\chi}'_k \overline{\chi}_k (1 - \overline{\chi}_k) \mathcal{H}^{n-1}(\{h = t\}) \, dt + \int_{t=0}^{\eta_k} c_k \mathcal{H}^{n-1}(\{h = t\}) \, dt.$$

As $p \in SBV$. So, $t \rightarrow \mathcal{H}^{n-1}(\{h = t\})$ is continuous at $t = 0$ and converges to $\mathcal{H}^{n-1}(S_p)$ with theorem ??. Thus, the second term converges to 0. Applying Fatou lemma gives

$$\begin{aligned} \limsup F_{\varepsilon_k}(p_k) &\leq \mathcal{H}^{n-1}(S_p) \limsup \int_{t=0}^{\eta_k} \frac{3}{4} \overline{\chi}'_k (1 - \chi_k^2) \, dt \\ &\leq \mathcal{H}^{n-1}(S_p) \int_0^1 6s(1-s) \, ds \\ &\leq \mathcal{H}^{n-1}(S_p). \end{aligned}$$

□

4 Convergence of solutions

In this section we prove an existence result for the minimizing problem of E_ε , with $\varepsilon > 0$ fixed; we set p_ε such solution. Then, we show the convergence a.e. of an extracted subsequence $(p_{\varepsilon_k})_{\varepsilon_k \in \mathbb{N}}$, with $\varepsilon_k \rightarrow 0^+$, to a binary function $p \in SBV(\Omega)$. To demonstrate that, we use the Γ -convergence result proved in section ??.

4.1 Lower semi-continuity of E_ε

For $\varepsilon > 0$ fixed, we can find a minimizer of E_ε on $W_b^{1,2}(\Omega)$. Contrary to E , the functional E_ε is lower semi-continuous for the usual topology.

Theorem 4.1. *Let $\varepsilon > 0$, the problem $(\mathcal{P}_\varepsilon)$ (??) admits solutions. More precisely, if $(p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ is a minimizing sequence of E_ε , then there exists a sub-sequence $(p_{k_l})_{l \in \mathbb{N}}$ converging a.e. to $p \in W^{1,2}(\Omega)$ such that*

$$E_\varepsilon(p) = \lim_{l \rightarrow \infty} E_\varepsilon(p_{k_l}) = \min \left\{ E_\varepsilon(q) : q \in W_b^{1,2}(\Omega) \right\}.$$

Proof. Let $(p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ be a minimizing sequence of E_ε . In particular, the sequence $(E_\varepsilon(p_k))_{k \in \mathbb{N}}$ is bounded. Since

$$9\varepsilon\beta \|\nabla p_k\|_{L^2(\Omega)}^2 \leq E_\varepsilon(p_k)$$

and

$$\|p_k\|_{L^2(\Omega)}^2 \leq \|p_k\|_{L^\infty(\Omega)} \mathcal{L}^n(\Omega) \leq \mathcal{L}^n(\Omega),$$

then this sequence is bounded in $W^{1,2}(\Omega)$. So, there exists a subsequence $(p_{k_l})_{l \in \mathbb{N}}$ which weakly converges to $p \in W^{1,2}(\Omega)$. The functional $q \rightarrow \int_\Omega |\nabla q|^2$ is lower semi-continuous for the weak topology of $W^{1,2}(\Omega)$. According to Fatou lemma, the functionals

- $q \rightarrow \int_\Omega (q - g)^2$
- $q \rightarrow \int_\Omega q^2(1 - q)^2$

are lower semi-continuous for the topology of the a.e. convergence. Then, we may conclude

$$E_\varepsilon(p) \leq \liminf_{l \rightarrow \infty} E_\varepsilon(p_{k_l}).$$

Since $(p_k)_{k \in \mathbb{N}}$ is a minimizing sequence then

$$E_\varepsilon(p) = \lim_{l \rightarrow \infty} E_\varepsilon(p_{k_l}) = \min \left\{ E_\varepsilon(q) : q \in W_b^{1,2}(\Omega) \right\}.$$

□

4.2 Compactness result of $(\mathcal{P}_\varepsilon)_{\varepsilon>0}$

According to ??, there exists p_ε solution of $(\mathcal{P}_\varepsilon)$. For numerical applications, we need the convergence of the solutions $(p_{\varepsilon_k})_{k \in \mathbb{N}}$ for any $\varepsilon_k \rightarrow 0^+$ to a solution of (\mathcal{P}) . In this section, we prove that this family is compact in the following sense.

Theorem 4.2. *Let $(\varepsilon_k)_{k \in \mathbb{N}}$ be a sequence converging to 0^+ and let $(p_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ be such that for any $k \in \mathbb{N}$, p_k is a minimizer of E_{ε_k} . Then, there exists a subsequence $(p_{k_l})_{l \in \mathbb{N}}$ which converges a.e. to $p \in \mathbb{B}(\Omega)$. Moreover, we have:*

- i) $p(x) \in \{0; 1\}$ a.e. $x \in \Omega$,
- ii) $p \in SBV(\Omega)$ and $\mathcal{H}^{n-1}(S_p) < +\infty$,
- iii) p is a solution of (\mathcal{P}) .

This result also prove that the space $SBV(\Omega; \{0; 1\})$ is "optimal" for the previous Γ -convergence result: it is the largest domain for which this result is satisfied.

Proof. Let $q \in SBV(\Omega)$ an arbitrary function such that q takes its values in $\{0; 1\}$ and $\mathcal{H}^{n-1}(S_q) < \infty$. According theorem ??, there exists a sequence $(q_k)_{k \in \mathbb{N}}$ such that $(E_{\varepsilon_k}(q_k))_{k \in \mathbb{N}}$ converges to $E(q)$. In particular, the sequence $(E_{\varepsilon_k}(q_k))_{k \in \mathbb{N}}$ is bounded, we denote M its higher bound. Since p_k is a minimizer of E_{ε_k} for any k then $(E_{\varepsilon_k}(p_k))_{k \in \mathbb{N}}$ is bounded by M too. We set $c_k = 3p_k^2 - 2p_k^3$. Note that $c_k \in W^{1,2}(\Omega)$ and that the chain rule gives $\nabla c_k = 6\nabla p_k p_k(1 - p_k)$, so we have

$$\begin{aligned} \int_{\Omega} |\nabla c_k| &= 6 \int_{\Omega} |\nabla p_k| p_k(1 - p_k) dx, \\ &\leq \int_{\Omega} 9\varepsilon_k |\nabla p_k|^2 dx + \int_{\Omega} \frac{p_k^2(1 - p_k)^2}{\varepsilon_k} dx, \\ &\leq \frac{M}{\beta}. \end{aligned}$$

Thus $(c_k)_{k \in \mathbb{N}}$ is bounded in $W^{1,1}(\Omega)$. So, there exists a subsequence $(c_{k_l})_{l \in \mathbb{N}}$ which converges a.e. to $c \in \mathbb{B}(\Omega)$. According that $x \rightarrow 3x^2 - 2x^3$ is a bicontinuous isomorphism from $[0, 1]$ to itself, there exists $p \in \mathbb{B}(\Omega)$ such that $(p_{k_l})_{l \in \mathbb{N}}$ converges a.e. to p . We have

$$\forall k \in \mathbb{N}, \quad \int_{\Omega} \frac{p_k^2(1 - p_k)^2}{\varepsilon_k} dx \leq \frac{M}{\beta}.$$

As $(\varepsilon_k)_{k \in \mathbb{N}}$ converges to 0^+ , Fatou lemma yields

$$\int_{\Omega} p^2(1 - p)^2 dx = 0,$$

so that $p(x) \in \{0; 1\}$ a.e. $x \in \Omega$.

Let us prove ???. As

$$\forall k \in \mathbb{N}, \quad E_{\varepsilon_k}(p_k) \leq M.$$

then $F_-(p, \Omega) \leq M < +\infty$.

Let $\nu \in \mathbb{S}^{n-1}$ be a fixed vector, and $(r_k)_{k \in \mathbb{N}} \subset W_b^{1,2}(\Omega)$ such that

$$\begin{cases} r_k \xrightarrow{\text{a.e.}} p, \\ F_{\varepsilon_k}(r_k, \Omega) \rightarrow F_-(p, \Omega). \end{cases}$$

Since $r_k \in W^{1,2}(\Omega)$, then $(r_k)_x$ (defined by ??) belongs to $W^{1,2}(\Omega_x)$ and we have:

$$\langle \nabla r_k(x + t\nu), \nu \rangle = \nabla(r_k)_x.$$

As

$$\int_{\Omega} \left(9\varepsilon_k |\langle \nabla r_k, \nu \rangle|^2 + \frac{r_k^2(1-r_k)^2}{\varepsilon_k} \right) dx \leq F_{\varepsilon_k}(r_k, \Omega).$$

Fubini theorem gives

$$\int_{\Omega_\nu} \int_{\Omega_x} \left[9\varepsilon_k |\langle \nabla r_k(x + t\nu), \nu \rangle|^2 + \frac{r_k^2(1-r_k)^2}{\varepsilon_k} \right] dt d\mathcal{H}^{n-1}(x) \leq F_{\varepsilon_k}(r_k, \Omega).$$

and

$$\int_{\Omega_\nu} F_{\varepsilon_k}^1((r_k)_x, \Omega_x) d\mathcal{H}^{n-1}(x) \leq F_{\varepsilon_k}(r_k, \Omega).$$

We apply Fatou lemma to get

$$\begin{aligned} \int_{\Omega_\nu} \liminf F_{\varepsilon_k}^1((r_k)_x, \Omega_x) d\mathcal{H}^{n-1}(x) &\leq F_-(p, \Omega), \\ \int_{\Omega_\nu} F_-^1((p_x), \Omega_x) d\mathcal{H}^{n-1}(x) &\leq F_-(p, \Omega). \end{aligned}$$

We deduce that $F_-^1((p_x), \Omega_x) < +\infty$ is finite \mathcal{H}^{n-1} -a.e. $x \in \Omega_\nu$. Otherwise, $((r_k)_x)_{k \in \mathbb{N}}$ converges to p_x a.e. on Ω_x and p_x takes its values on $\{0; 1\}$ \mathcal{H}^{n-1} -a.e. $x \in \Omega_\nu$. According to lemma ??, we have

$$p_x \in SBV(\Omega_x)$$

for \mathcal{H}^{n-1} -a.e. $x \in \Omega_\nu$. Moreover, we have proved that $\mathcal{H}^0(S_{p_x} \cap \Omega_x) \leq F_-^1(p_x, \Omega_x)$ and $\nabla p_x = 0$, so we have

$$\int_{\Omega_\nu} \left\{ \int_{\Omega_x} |\nabla p_x| dt + \mathcal{H}^0(S_{p_x}) \right\} d\mathcal{H}^{n-1}(x) < +\infty.$$

Now, the conditions of theorem ?? are satisfied. We can conclude that $p \in SBV(\Omega)$ and $\mathcal{H}^{n-1}(S_p) < +\infty$.

Let us prove ???.

□

5 Conclusion

We have shown in section ?? that $(E_\varepsilon)_\varepsilon$ Γ -converges to E (theorem ??) in SBV and this is the best we can have (theorem ??). Furthermore, we have shown that this approximation is suitable for numerical experiments since the solutions of $(\mathcal{P}_\varepsilon)$ are approximations of (\mathcal{P}) (theorem ??).

Practically, we replace the problem

$$(\mathcal{P}): \text{Min} \{E(p) : p \in SBV(\Omega), \text{ and } p \text{ takes its values in } \{0, 1\}\}$$

by the problem

$$(\mathcal{P}_\varepsilon): \text{Min} \{E_\varepsilon(p) : p \in W_b^{1,2}(\Omega)\}$$

with ε fixed and small. In the companion paper [?], we study this approximate problem with the specific constraints for thin tubes.